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ATTENUATION OF RADIO FREQUENCY WAVES THROUGH THE EARTH*

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ABSTRACT

Evidence has been presented by several investigators indicating the possibility that radio waves penetrate sufficiently deep into the earth to be useful in prospecting for oil.

Conventional electromagnetic theory used with normal values of the earth constants indicates, however, that the attenuation is too great to allow the signal to be used after propagation through significant distances of shale.

To settle the above question an experiment was conceived and carried out in which the signal level in the earth was measured at various distances from a battery-operated transmitter operating at 1,652 kc suspended in an uncased, mud-filled hole by a mud-saturated rope. The mud resistivity was matched to that of the 40 foot thick shale section used in order that the entire immediate region would be as nearly as possibly homogeneous. The receiver was also battery-operated and suspended by a cable in other similar mud-filled holes at various distances from the first hole.

The attenuation constant in shale was found to be 0.231 nepers/foot (2 db/foot), which is much too large to give any hope of deep penetration. A few measurements in a limestone section gave a value of 0.086 nepers/foot, which is also too large to be useful. Although these values are quite high, they are lower than theory predicts for these earth resistivities by a factor of about two.

ATTENUATION OF RADIO FREQUENCY WAVES THROUGH THE EARTH

A. Purpose of the Investigation

In spite of considerable evidence in the literature to the contrary,[1,2,3] some evidence is found in the literature which suggests the possibility of propagating radio waves through the earth for a considerable distance.[4,5,6] This possibility has been difficult to accept in view of its apparent conflict with well established electromagnetic theory. Briefly, the theoretical attenuation (using normally accepted values for earth constants, such as conductivity $\geqq 1/20$ mho/meter, relative dielectric constant $\leqq 80$, and relative magnetic permeability $= 1$) is so great that a radio wave would be hopelessly diminished in traveling through less than 100 feet of shale.

If, however, an experimental measurement of the attenuation of a radio wave in the ground should give a sufficiently low value, then it would seem quite

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possible that a method for exploring deep into the earth in search of oil could be developed. On the other hand, if experiment definitely showed a high attenuation, and if the experimental results were beyond question in value or interpretation, then radio frequency prospecting as a tool for investigating conditions at depth would be eliminated, at least for those conditions of frequency, earth resistivity, etc., investigated. This would not mean that fair propagation could not be achieved through extremely dry earth, as would theoretically be expected, but rather that it could not be achieved through the brine saturated earths commonly encountered at depths greater than a few hundred feet.

B. The Experiment

The experiment was designed to measure the attenuation of a radio wave in the earth in as straightforward a manner as possible. A battery-operated transmitter was lowered on a non-metallic rope into an uncased hole, about 100 feet deep, to the middle of a 40-foot-thick shale section (See Figure 1). In a second hole a receiver was lowered on a rope. It, too, was battery-operated, but an audio signal was sent to the surface via a shielded cable. The mud resistivity in each hole was made to be approximately equal to the average resistivity of the shale bed. (Shale resistivity measured at 1,000 cps; mud at 60 cps, see Figure 14.) The transmission medium should then appear homogeneous according to conventional electromagnetic theory.

Receiver output voltages were obtained for nine hole separations of from 5 to

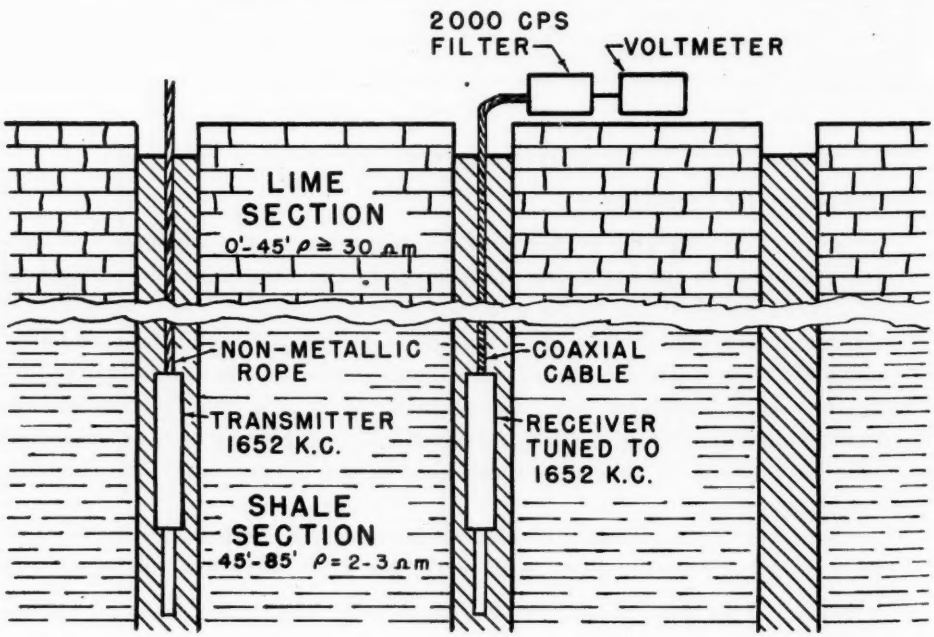

FIG. 1. Set-up used in measurement of signal decline of radio wave in the earth.

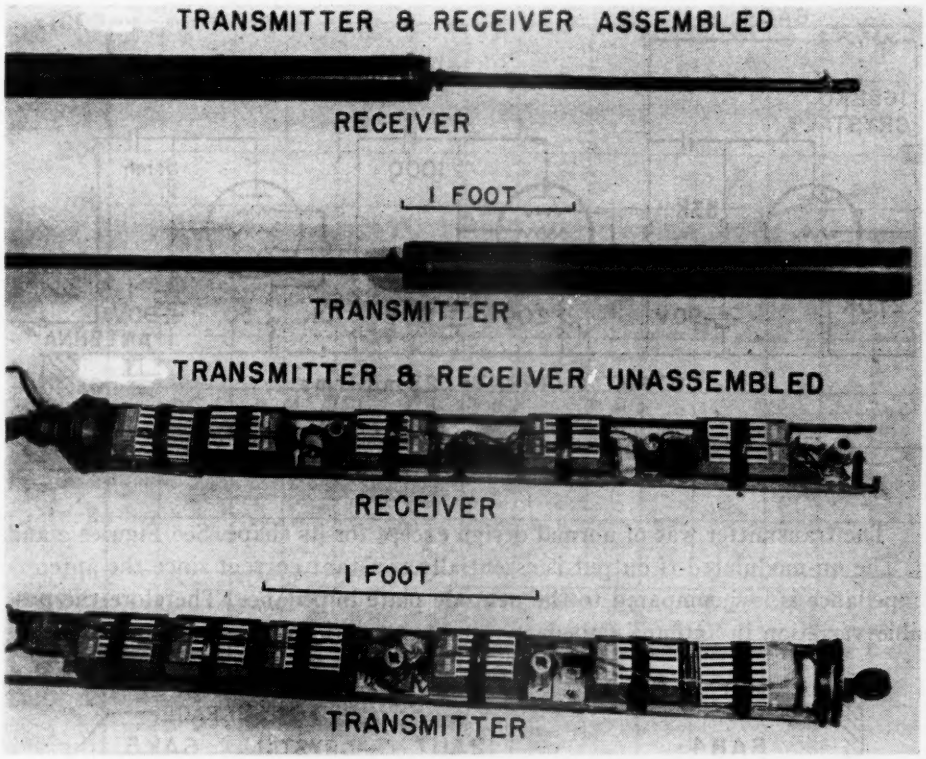

FIG. 2

155 feet. The signal decline was then compared to that calculated by theory. Also an approximate experimental value for the attenuation constant was obtained.

Even in this simple setup the field close to the transmitter is quite complex. Investigation, however, is theoretically limited to a region close to the transmitter due to the high theoretical attenuation. In order to be able to be sure of obtaining a measurable signal at a practical hole separation a very sensitive receiver with a low noise level was required.

The presence of the cable running to the receiver raised the question of how much it would contribute as an antenna to the receiver input, and, more importantly, of whether this signal contribution would vary with the length of cable in the hole. It was decided that these questions could and would be answered when the experiment was run and that in all probability no difficulty would result. As expected, the contribution of the cable as an antenna was limited to a relatively short length close to the receiver and there was little or no variation due to the length of cable in the hole. The energy path was definitely determined to be directly through the ground in all of the data as was shown by the fact that variations of a few feet in depth of the transmitter or receiver resulted in a rapid decline from the maximum received signal.

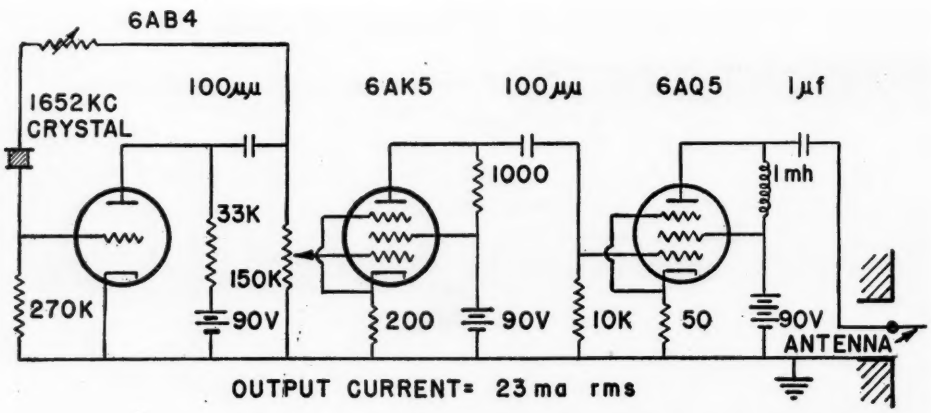

FIG. 3. Transmitter (sub-surface).

C. Equipment

The transmitter was of normal design except for its shape. See Figures 2 and 3. The un-modulated rf output is essentially constant current since the antenna impedance is low compared to the pentode plate impedance. Therefore the possible variation in antenna impedance due to variation in resistivity of the sur-

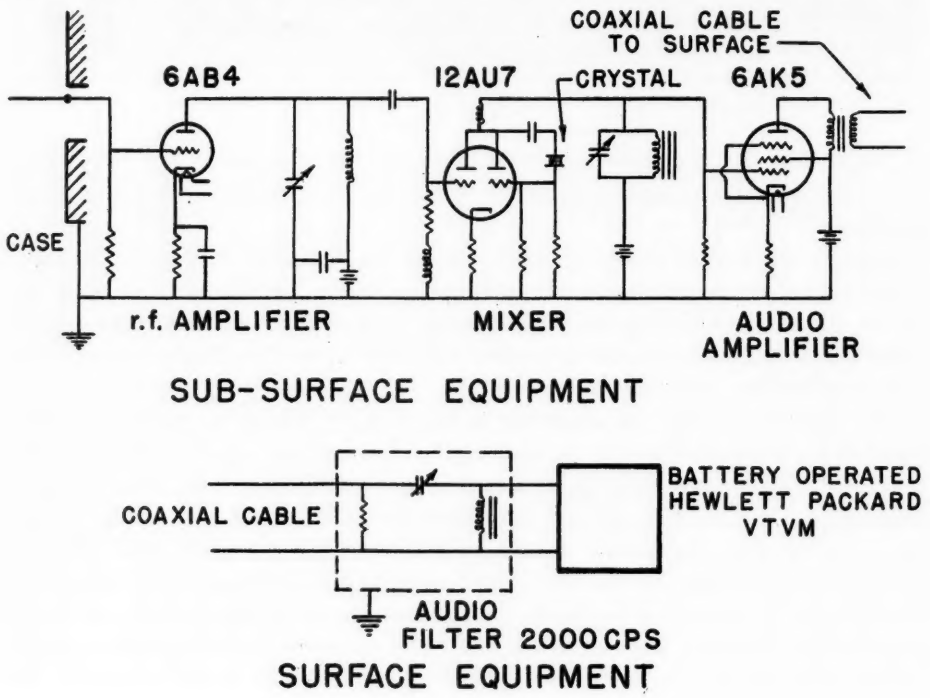

FIG. 4. Receiver.

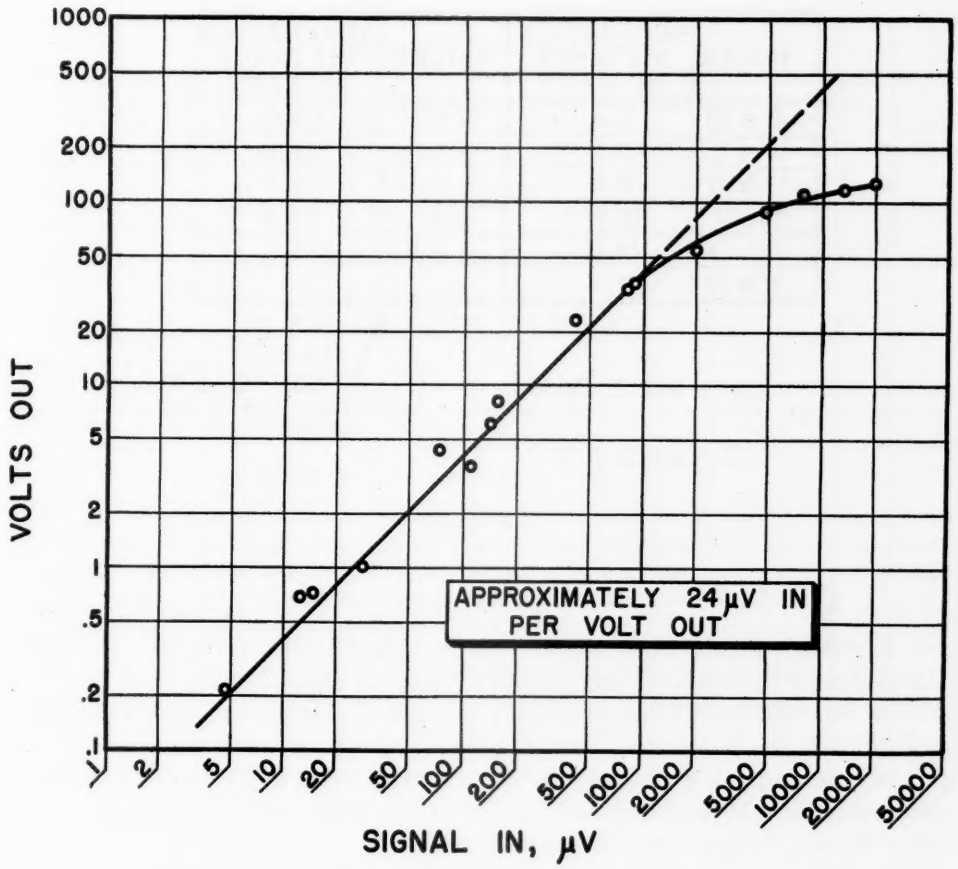

FIG. 5. Calibration of receiver sensitivity.

rounding medium could not affect the radiated power. Antennas and cases of both transmitter and receiver were insulated from the mud.

The receiver is a heterodyne type of much less conventional design. See Figures 2 and 4. The audio beat note of approximately 2,000 cps is sharply filtered at the surface. The center frequency of the surface filter is adjustable to allow for any possible frequency drift of either the crystal controlled transmitter or of the crystal controlled local oscillator. The over-all band width of the receiver is 20 cps at 1,652 kc. (There is, of course, also the image pass band of an additional 20 cps at 1,656 kc). The input tube is a high transconductance triode biased more than in normal service to reduce "shot noise." The input impedance is probably less than 100 ohms. All these things were helpful in reducing the noise level to about 0.2 microvolts input with the receiver in the ground.

The dual triode mixer was found necessary in order to avoid any direct capacitance between signal grid and oscillator grid. The receiver sensitivity calibra-

HOLES	SEPARATION DISTANCE IN FEET	HOLES	SEPARATION DISTANCE IN FEET
II & III	5.4	III & V	23.0
I & II	7.7	I & IV	24.6
I & III	10.3	II & V	27.3
IV & V	12.8	I & V	33.2
III & IV	14.9	I & VI	155
II & IV	17.4		

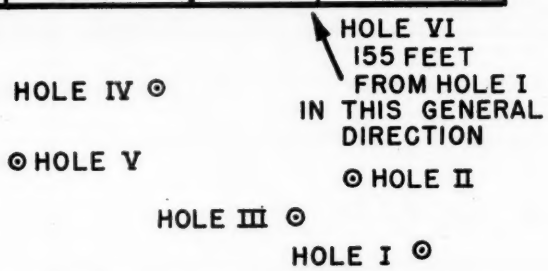

FIG. 6. Hole positions and separation distances.

tion is given in Figure 5. As can be seen the calibration is linear up to an output signal of more than 30 volts, but saturates badly for higher output voltages. Correction was required for the data taken at the two shortest hole separation distances.

The falling off of signal with time due to battery drain was obtained by taking readings in holes IV and V at three different times. This curve was used to adjust all of the data. Actually, this correction is minor.

TABLE I

EXPERIMENT NO. 1—MAIN DATA

Receiver Depth* Feet Approx.	Output Voltage of Receiver at Separation Distance Indicated			
	$d=5.4'$	$d=7.7'$	$d=10.3'$	$d=5.4'$
73	100	48		
71	102	50	13	
69	105	53	14	
67	107 (107)	54 (53)	15 (15)	
65	108	53	15.5	
63	104	51	13.8	
61	102	45	13.5	
59	101	50	15.8	
57	105	62	22	
55	113	67	23.2	
53	111	58	19	
43 } very approx.	122	70	43	
30 } very approx.	128	89		96 Instrument Stuck in Hole

* Transmitter at same depth as receiver.

TABLE II

EXPERIMENT NO. 2—MAIN DATA

Receiver Depth*	Voltage Output of Receiver at Separation Distance Indicated						
	10.3′	33.2′	155′	24.6′	12.8′	23′	14.9′
69′	22	.11	0†	.45	27	2.95	
67′	22.5	.10	0†	.46	26.5	2.8	14
65′	21	.09	0†	.40	25	2.48	13
time	12:45	12:56	1:02	1:06	1:10	1:14	1:19
25′	58	3.9	} Signal through limestone				
30′	61	3.2					
time	1:40	1:43					

* Transmitter at same depth as receiver.

† Measured at depths of 13′–20′. No signal above noise level of 0.007 volt output. Signal at 155′ was 0.13 volt with both instruments above ground level.

D. Earth Characteristics

A total of six holes were used in two experiments. One hole had to be abandoned between experiments because a reaming tool became stuck in the hole. The relative position of the holes is shown in Figure 6. Good resistivity logs were obtained in holes I, III, IV, and V. In general the earth was fairly high resistivity (about 30 ohm-meters) lime down to 45 feet. Then there was a 2 to 3 ohm-meter shale section down to 85 feet. The shale resistivity varied somewhat with depth in each hole and from hole to hole. The mud resistivity was pretty closely matched to that of the shale to avoid reflections at the walls of the hole.

E. Experimental Results

Most of the data is given in Tables I and II. At each depth the receiver was held at constant depth and the transmitter, at approximately the same depth, was moved up and down over a few feet to obtain a maximum reading. Also the receiver tuning was checked. Proof that the transmission was through the ground is afforded by the fact that at each receiver depth the maximum signal occurred with the transmitter at very nearly the same depth as the receiver. Also the data in Figure 7 show how much the signal falls off with a variation in transmitter depth relative to receiver depth. It is true that at the larger distances and when the receiver had not penetrated far into the shale it was noticed that having the transmitter up in the bottom of the lime gave the greatest signal of all since the signal could then travel most of the distance through the higher resistivity (and consequently lower attenuation) lime. But even in these cases a good maximum near the proper depth was always obtained.

A linear plot of the signal decline with distance is shown in Figure 8. The points plotted are all experimental. The solid curve is a plot of Equation (3) using an attenuation constant of 0.231 nepers/foot. This equation and value of the attenuation constant will be discussed in the next section.

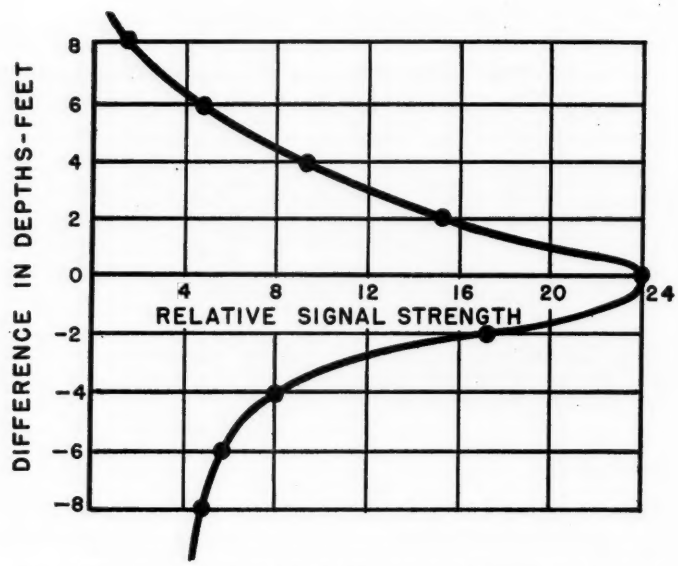

FIG. 7. Decline in signal with variation in depth of transmitter relative to receiver.
Receiver at 79′
Hole separation 10.3′

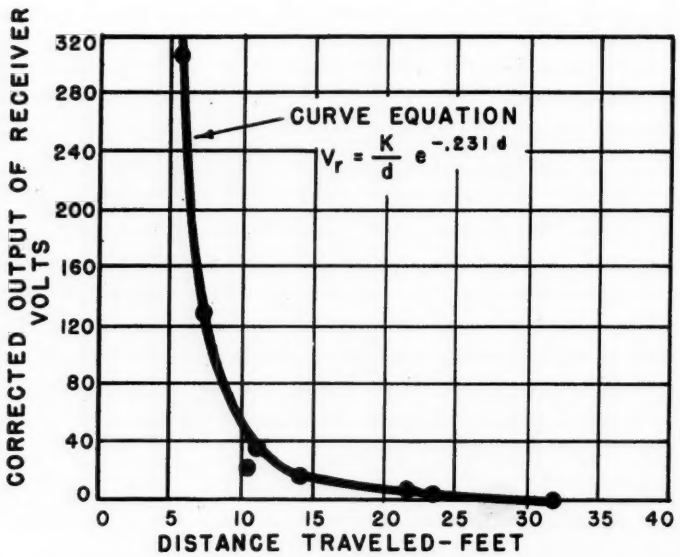

FIG. 8. Linear plot of measured signal decline with distance.

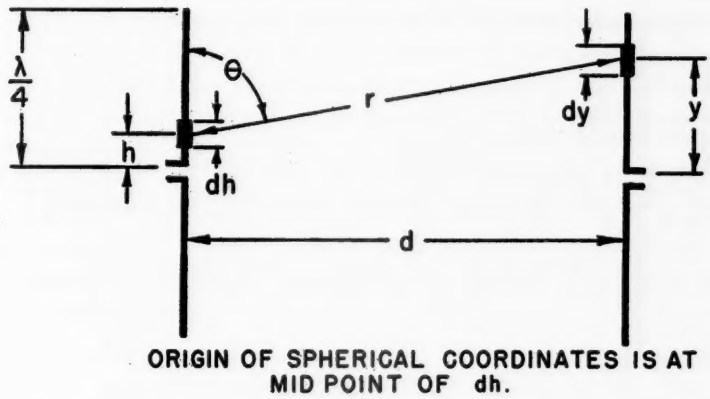

FIG. 9. Coordinates and terminology used in relation to equations for received signal.

F. Interpretation

The approximate theoretical received voltage if both receiver and transmitter have parallel, half-wave antennas possessing a common perpendicular bisector is:[7]

$$V_r \approx -\frac{I_0}{4\pi}\int_{-\lambda/4}^{+\lambda/4}\int_{-\lambda/4}^{+\lambda/4} e^{-\alpha r}e^{-j\beta r}\left\{(\sin^2\theta)\,\frac{j\omega\mu}{r}\right.$$

$$+(1-3\cos^2\theta)\left[\frac{(1+j)\left[\frac{\omega\mu}{2\sigma}\right]^{1/2}}{r^2}\right.$$

$$\left.\left.+\frac{1}{j\omega\epsilon_c r^3}\right]\right\}[e^{-\alpha|h|}\cos(\beta h)][e^{-\alpha|y|}\cos(\beta y)]\,dy\,dh. \quad (1)$$

See Figure 9 for the coordinate system used.

where $r=[d^2+(y-h)^2]^{1/2}$
$\theta=\cot^{-1}(y-h)/d$
$\sigma=$ conductivity in (ohm-meters)$^{-1}$
$V_r=$ received voltage
$\alpha=$ attenuation constant $\approx[\pi f\mu\sigma]^{1/2}$
$\beta=$ phase constant $\approx[\pi f\mu\sigma]^{1/2}$
} valid where $\sigma/\omega\epsilon\gg 1$. For our earth, $\sigma=1/2.16$, $\epsilon'=25$, $\sigma/\omega\epsilon=200$
$\lambda=$ wave length $=2\pi/\beta$
$\mu=$ magnetic permeability
$\epsilon_0=$ free space dielectric constant
$\epsilon'=$ relative dielectric constant

ϵ_c = equivalent dielectric constant of a conductor
$\epsilon_c = \epsilon[1 + \sigma/j\pi\epsilon]$
$\epsilon = \epsilon_0\epsilon'$

MKS units are used in these equations.

Equation (1) is too cumbersome for our use. Making some approximations ($r = d$, $\theta = 90°$) that are less serious than our experimental errors, gives:

$$V_r \approx K\left[\frac{jA}{d} + \frac{(1+j)B}{d^2} + \frac{C}{d^3}\right]e^{-\alpha d}, \tag{2}$$

where

$$A = \omega\mu; \qquad B = \left[\frac{\omega\mu}{2\sigma}\right]^{1/2}; \qquad C \approx \frac{1}{\sigma}.$$

An even more approximate but simpler equation is given below:

$$V_r \approx \frac{K'e^{-\alpha d}}{d}. \tag{3}$$

Equation (3) will be justified for use with the experimental data in determining the value of the attenuation constant α. In Figure 10 the slope of the signal decline versus distance curve as given by Equation (2) is compared to that given

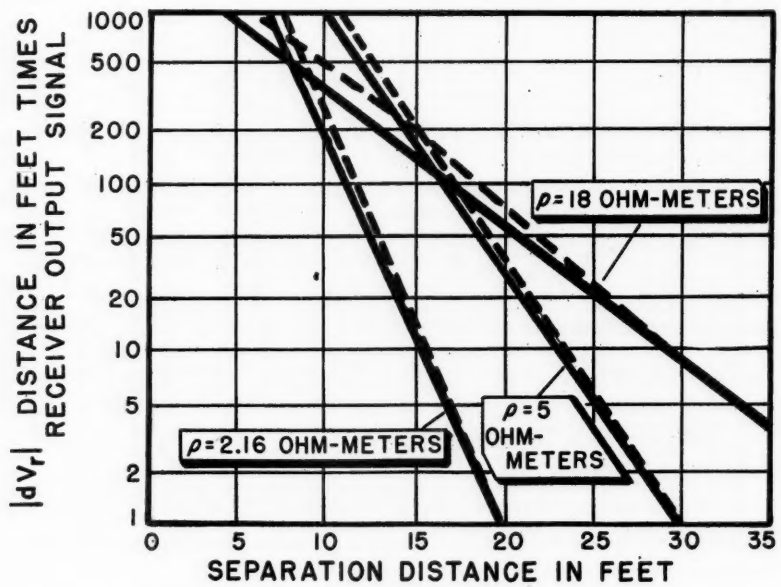

FIG. 10. Comparison of slopes using Eq. (3) as compared to Eq. (2).
Solid line = Eq. (3)
Dotted line = Eq. (2)

by the even simpler Equation (3). These pairs of curves were made to cross at $d=30'$, by adjustment of K and K', since the actual signal level is of no importance but what is important is the manner in which signal declines with distance. As can be seen the variation in slope is small for a resistivity of 18 ohm-meters or less and is negligible for $\rho=5$ ohm-meters or less.

What is wanted is a value of the attenuation constant α. Since α varies with resistivity and since the resistivity varies somewhat from hole to hole correction factors on the distances used in the experimental data should be used. These corrected "apparent" distances d' were calculated using a base value pf $\rho_0=2.16$ ohm-meters, and a formula

$$d' = d\left[\frac{2.16}{\rho}\right]^{1/2}. \tag{4}$$

The data were also corrected for signal decline with time. Both these corrections were minor refinements.

The next thing to be done is to find the experimental attenuation constant in nepers/foot. Each time a value of the attenuation constant is given there will also be given the corresponding maximum depth that could be penetrated (and still be detectable) by a plane wave starting at the surface with an energy level of ten-million watts, totally reflected at this maximum depth, totally received at the surface with a receiver capable of detecting one millionth of one billionth of a watt.

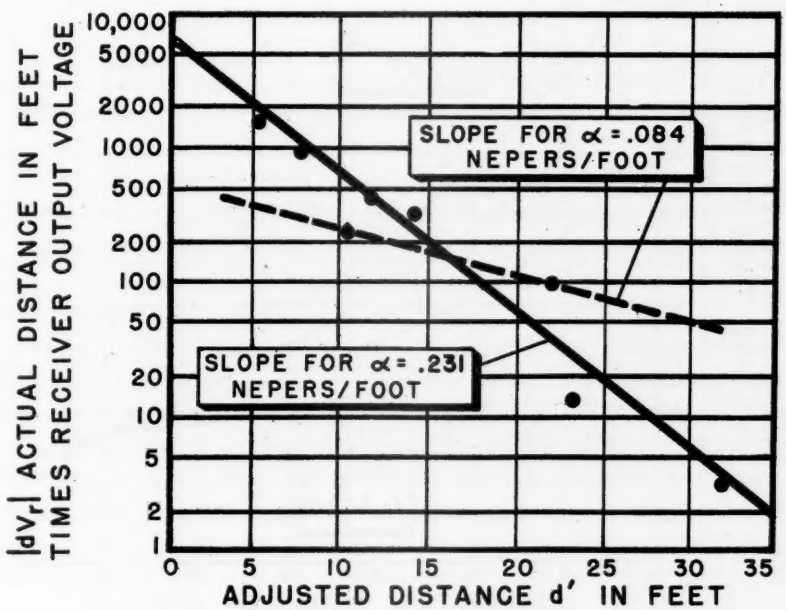

FIG. 11. Experimental signal decline with distance.

TABLE III

ATTENUATION FACTOR

Factor $e^{\alpha d}$ for Various Distances Expressed in Feet and for Possible α Expressed in Nepers/foot

d(feet)	α=0.231	α=0.084	α=0.0723
10	1.01×10^{1}	2.32	2.06
20	1.013×10^{2}	5.37	4.24
40	1.026×10^{4}	28.8	18
100	1.0667×10^{10}	4430	1380
200	1.138×10^{20}	1.96×10^{7}	1.91×10^{6}
400	1.295×10^{40}	3.84×10^{14}	3.66×10^{12}
1,000	1.908×10^{100}	2.88×10^{36}	2.57×10^{31}

These penetration depths will obviously be quite optimistic.

In Figure 11 the experimental data is so plotted that according to Equation (3) the signal decline curve should be a straight line with a slope equal to the attenuation constant. The solid line in Figure 11 does fit the data nicely and is straight as predicted. From its slope an experimental attenuation constant of 0.231 nepers/foot is obtained. This corresponds to a maximum penetration depth of only 60 feet. The theoretical value of the attenuation contant calculated from earth constants is 0.53 nepers/foot which would allow a maximum penetration depth of 26 feet.

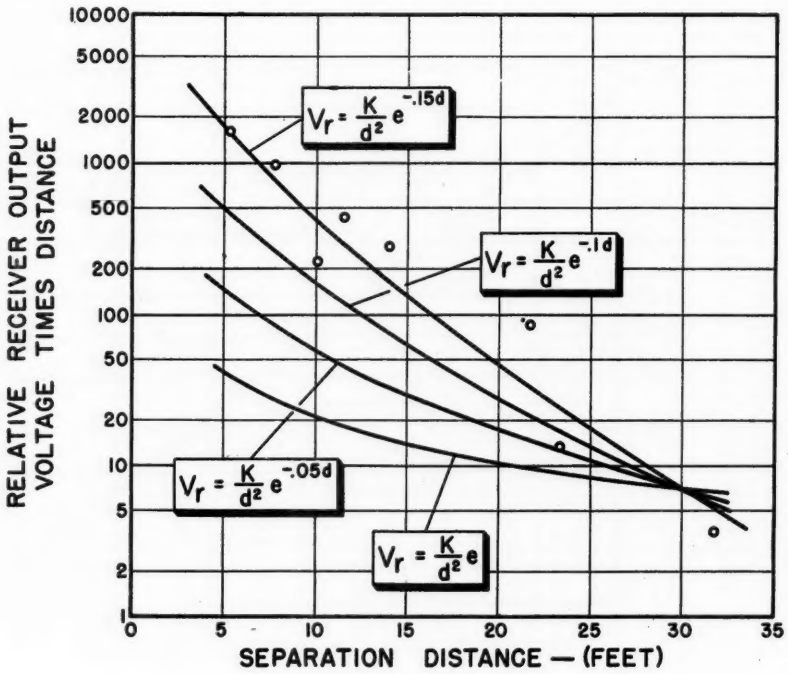

FIG. 12. Required attenuation constant assuming correct divergence factor is $1/d^2$.

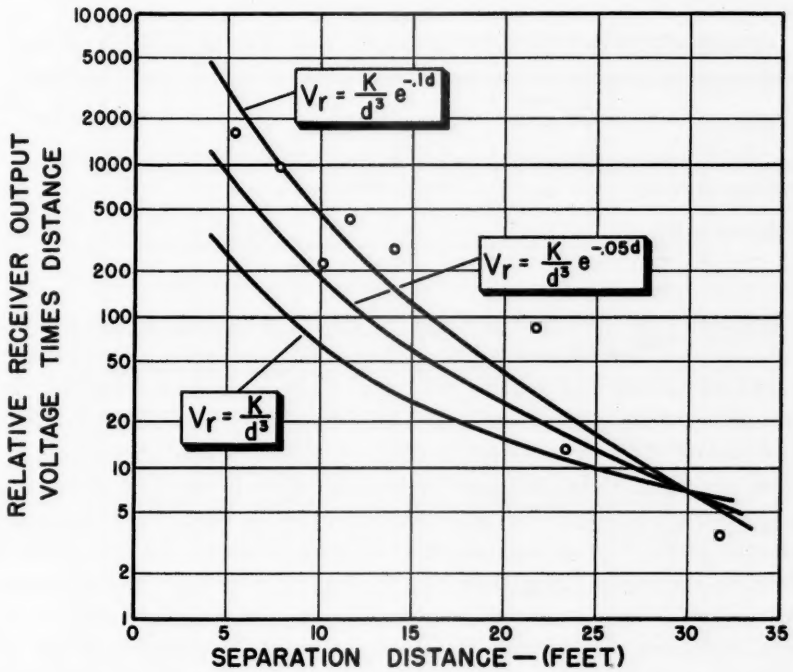

FIG. 13. Required attenuation constant assuming correct divergence factor is $1/d^3$.

Admittedly there is some scatter in the points, but even if the slope of the dotted line in Figure 11 is used to determine α a value of $\alpha = 0.084$ nepers/foot is obtained. This corresponds to a maximum penetration depth of 165 feet. A glance at Table III will suffice to demonstrate how hopelessly great the attenuation factor becomes.

The scatter of points in Figure 11 is not too surprising. First, the hole separations as measured at the surface might differ from the actual separations at depth by possibly two feet. Also the resistivity logs indicate that the shale is streaked with lime. A good lime coupling may exist between one pair of holes and may pinch out before reaching others.

Suppose for a minute that in Equation (2) instead of A/d being the dominant term that $B(1+j)/d^2$ is dominant. In this case the divergence factor would be larger requiring a smaller attenuation factor. In Figure 12 the signal decline for this divergence is plotted for several values of α. It is seen however that even so an attenuation constant of 0.15 nepers/foot would be required to fit the data which would allow a maximum penetration depth of 93 feet.

Even if C/d^3 in Equation (2) is considered to be the dominant term (i.e. a divergence factor of $1/d^3$) an attenuation constant of 0.10 nepers/foot would be required (See Figure 13). This corresponds to a maximum penetration depth of 139 feet.

TABLE IV

COMPARISON OF QUALITY OF FIT OF SEVERAL CURVES TO EXPERIMENTAL DATA

	$\frac{Ke^{-0.231r}}{r}$	$\frac{K}{r^3}$	$\frac{K}{r^4}$	$\frac{K}{r^5}$	$\frac{K}{r^6}$
$\sum$ Deviations of Points	+ 0.1	+ 0.1	+ 0.4	0.0	0.0
$\sum$ |Deviations of Points|	15.3	36.1	28.4	29.8	42.8

It has been suggested that perhaps the theory is entirely wrong and that perhaps the divergence is an even higher power function. Curves were plotted, to the same scale as was used in plotting the data, of signal declines assuming no attenuation but assuming divergence factors of $1/r^3$, $1/r^4$, $1/r^5$, and $1/r^6$. None of these curves fitted our data over the entire range of distances used (See Table IV).

From the signal data obtained for two distances in the lime an approximate value of $\alpha = 0.0723$ nepers/foot was calculated for the lime. Since no signal could be detected at 155 feet in the lime this value must not be much too high if any. It should be emphasized that Hole No. VI was not salted (i.e. the mud resistivity was not lowered from a natural value of about 14 ohmmeters to about 2.5 ohmmeters). But since the attempt to measure a signal level was through the high resistivity lime this should have aided reception rather than hindered it. The receiver input signal level in limestone at 155 feet was less than 0.2 microvolts and the field strength in the medium less than 0.1 microvolts per meter.

The attenuation constant value of 0.231 nepers/foot obtained from Figure 11 would theoretically indicate a resistivity of 11 ohmmeters as compared to the measured value of 2.16 ohmmeters at 1,000 cycles/sec. Possibly the radio frequency resistivity is that much greater. If the resistivity were 2.1 ohmmeters a dielectric constant of 13,000 times that of free space would give this attenuation. This is deemed to be very unlikely.

Actually, the literature seems to indicate that the resistivity of earth and sea water decreases as frequency is increased from low frequency up to 10 mc[1,8,9] Smith-Rose gives a typical curve for 14 English soils obtained at depths up to 300 feet which shows a resistivity decrease of about 20 percent from low frequency to 1.6 mc. See Figure 14. The relative dielectric constant at 1.6 mc is about 25. A measurement of drilling mud resistivity at 60 cycles and at 1.6 mc indicated that the conductivity increased about 25 percent, which is fair agreement with Smith-Rose's data. Measurements of dielectric constant though not too accurate indicated that the dielectric constant could not be higher than 80.

It will be noted that our experimental value for the attenuation constant differs from the theoretical by a factor of 2. The presence of lime in the shale may possibly be more effective in increasing the transmission of rf energy than in increasing the average resistance measured by our three electrode arrangement used in logging these holes.

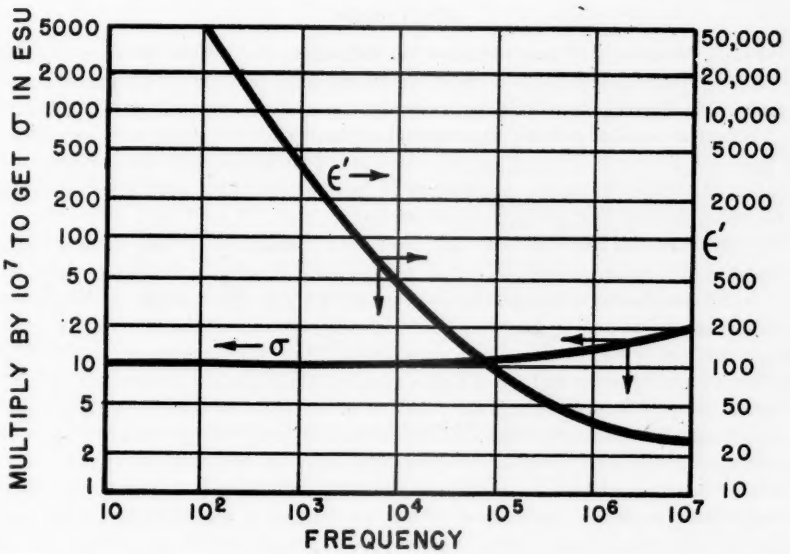

FIG. 14. Variation in σ and ϵ' with frequency.
(Curve taken from R. L. Smith-Rose[8].)

G. Conclusions

It is believed that this experiment gives definite proof that a 1,652 kilocycle wave will be so greatly attenuated in shale that propagation to depths of several hundred feet is not possible. In our limestone the attenuation is also so large that no great penetration can be achieved.

If we exclude the possibility of some unknown, exceedingly optimum frequency, then radio frequency prospecting would appear to be limited to very shallow depths or to rare, exceedingly dry areas.

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DISCUSSION

HERBERT A. MORRISS, JR.* and FIELDING M. MCGEHEE, JR.*: While the foregoing paper possesses an air of verisimilitude difficult to resist, we cannot agree that the work reported constitutes a crucial experiment denying the possibility of propagation to depths exceeding several hundred feet.

The mechanical simplicity of the experimental apparatus and the direct measurement of a field gradient from hole to hole both favor the determination of a relevant earth transmission parameter. With greater radiated power, facilitating a larger range of observations, valid attenuation values for shale could certainly have been secured in this manner.

As Mr. Pritchett has conceded, the field close to a transmitter is quite complex. Immersion of a transmitter and its associated antenna in a dissipative or semi-conducting medium adds considerably to this complexity, creating radiation conditions about which almost nothing directly pertinent has been published to date. However, it can be safely stated that the source of radiation in this case was not confined to the metallic dipole elements described but extended to the complete system of conduction currents flowing in the shale as a result of the potentials impressed upon the dipole. This system of current sheets must have enveloped all of the points at which observations were made, therefore the values taken actually reflect the interference pattern which prevails within the structure of an antenna array rather than well-known phenomena external to a radiating source.

Convinced of the existence of interference minima by the appreciable scatter of the Atlantic data in the vicinity of 10 feet, 23 feet and 33 feet, we felt that it was necessary to reconstruct the experiment in such a manner as to permit a more detailed examination of the field around the transmitter. We reasoned that a vertical plane could be passed through the transmitting and receiving holes so as to divide the dissipative medium into two symmetrical half-spaces; and that one of these halves could be replaced by a non-conducting half-space, such as air, without materially altering the induction effects to be observed along the interface. In principle we rotated the holes from the vertical to a horizontal position, passed a bisecting plane through them and removed the upper half of the earth; or, in actuality, we transmitted between parallel trenches dug in the surface of a very moist earth. Following Pritchett's choice of radio frequency and using the same length antenna elements embedded in mud at the base of a transmitting trench approximately 20 inches deep, we made a survey analogous to Atlantic's over the range of 6 to 50 feet.

In the broken line plotted on the upper graph of Figure 1 can be seen the close agreement of these data with five of the eight points reported by Pritchett. Elevating our receiving antenna directly upward to a point only 20 inches above ground level, we found the signal in air to be less than six percent of the signal in ground over the traverse 7 feet to 25 feet from the transmitter. Beyond 25 feet the signal in air was blow the linear range of our receiver.

Having satisfied ourselves that we were working under conditions analogous to the Atlantic experiment and that the contribution from air path transmission was too small to affect the gross character of our results, we proceeded to a detailed investigation of the fine structure of the field by probing the voltage gradients at 1-foot intervals out to 82 feet. In Figure 1 these results are plotted as a solid line. A pronounced minimum appears in the vicinity of 11 feet which can be said to bring us into agreement with six out of Pritchett's eight observations. Failure to secure strong minima at 23 feet and 33 feet may be due to lack of water saturation or of homogeneity in the soil over which we were working.

In the lower graph of Figure 1 we repeat the data of the upper graph using as our ordinates the product of signal voltage and the cube of distance rather than the first power. Despite the complications introduced by the presence of a superimposed interference pattern, our data are obviously fitted by the inverse cube geometry characteristic of an induction field. If Atlantic's data were more extensive, we feel that they too would unmistakably display the same fundamental divergence.

Upon the inverse cube geometry which plots as a horizontal line in the lower graph, it is possible to impose some attenuation and still remain within the data we observed. Although we do not believe that attenuation measurements should be carried out in a region where such complex geometry

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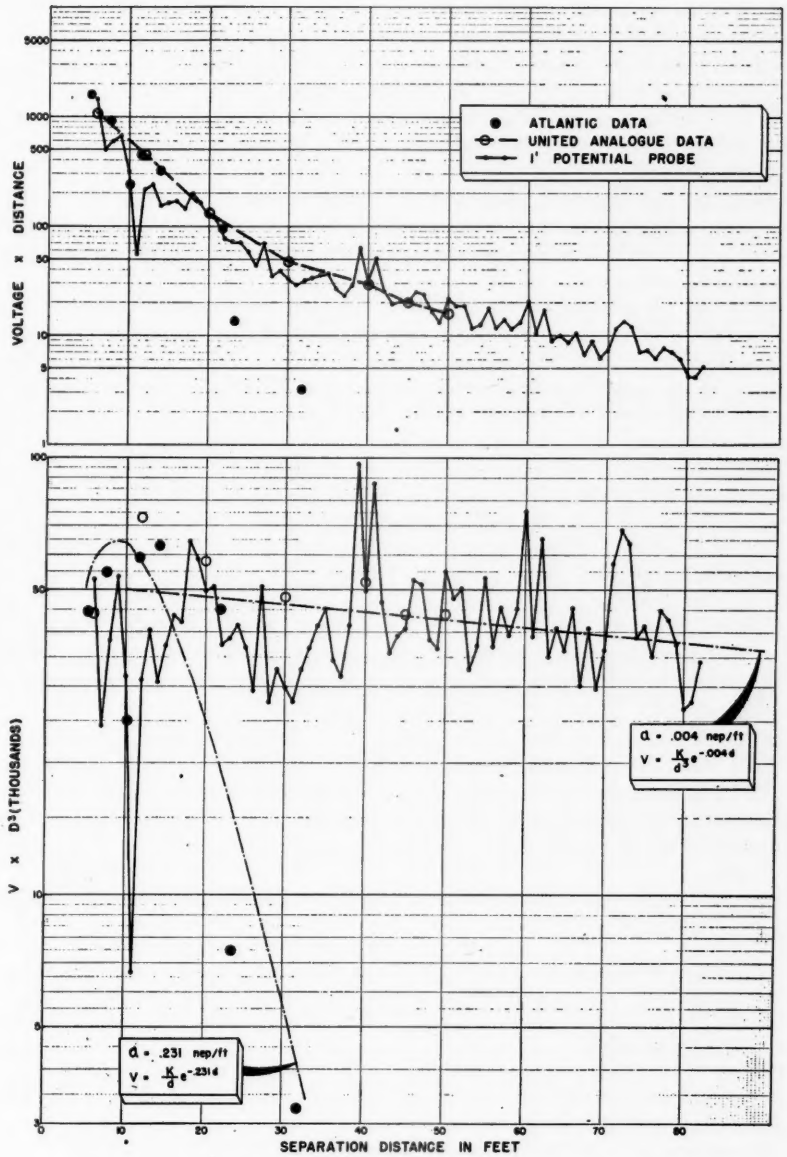

FIG. 1. Comparison of data for experimental signal decline with distance.

prevails, we cannot object to a value as high as 0.004 neper/ft. for the highly dissipative media in which we and Pritchett were working. For an acceptable over-all path attenuation of 18 nepers this would yield a useful transmission path in the order of 4,500 feet. Incidentally, using Pritchett's power level of transmission this value would lead to an observable signal of about 0.0075 volts at 155 feet which is close to the noise level of 0.007 volts reported by Pritchett for his experiment.

If we were inclined to serious consider an attenuation value as high as Mr. Pritchett's $\alpha = 0.231$ neper/ft we would at once question the compatibility of this value with the contention that his observations were all made in the so-called "radiation zone" of the transmitting antenna where inverse distance geometry prevails.

In showing the equivalence of phase and attenuation constants, Pritchett has established a finite value for wavelength in the medium, i.e., $\lambda = (2\pi/\alpha) = (2\pi/0.231) = 27.2'$. His range of observations (5.4 feet to 33.2 feet) may at once be expressed in terms of wavelengths, or 0.22 λ to 1.22 λ from the transmitting antenna.

The region near the antenna, extending to about one-tenth wavelength, is commonly called the induction zone and may be treated with small error by assuming that the field strength falls off as the third power of the distance. The region far from the antenna, from about ten wavelengths to infinity and called the radiation zone, may be treated accurately by assuming a function depending on the inverse first power of the distance. In the space between these two, the intermediate zone, field strength computations are not nearly so simple. To quote one authority on the subject, "It is well to note that it is illogical to attempt to interpret the properties of the intermediate zone in terms of a combination or superposition of the properties of the near and far zones."[1]

It may readily be seen from the brief wavelength calculations above that Mr. Pritchett's data must actually have been taken in this complex region. Since the logical consequence of Mr. Pritchett's calculations places him in the intermediate zone of his antenna, neglecting any complications due to conduction currents in the earth, it follows that one may not assume any fixed or average value for "n" in the field strength equation, $V = K\epsilon^{-\alpha d}/d^n$ nor even suppose that it will have the same form at all points in the 5.4 to 33.2 foot range. The divergence gradient, $1/d^n$, being variable and unknown throughout, we should not expect that eight randomly chosen points would be indicative of a true attenuation constant.

We find much that is interesting and instructive in the Atlantic experiment. While we cannot concur in Mr. Pritchett's conclusion by several orders of magnitude, we would commend him for reopening scientific discussion on the fundamental question of whether electromagnetic energy can be propagated for useful distances through the earth's mantle. We hope that the question will remain open until radiation in and propagation through semi-conducting media are more thoroughly understood by all of us.

Permission of United Gas Corporation to publish the foregoing results of experimental work is gratefully acknowledged.

AUTHOR'S REPLY TO DISCUSSION OFFERED BY MORISS AND MCGEHEE

Messrs. Morriss and McGehee have raised questions as to the validity of the author's conclusions because of the following points:

1. Standing waves in the medium may cause errors in computing the attenuation.
2. The author worked in the "complex region" from 0.1 to 10 wavelengths from the antenna for which the interpretation is not simple.

For reasons given below we believe these objections are not valid:

Mr. Morriss in his theory of the current distribution in a conducting medium in response to a dipole antenna visualizes paths of high and low input impedances corresponding to path lengths of $n\lambda/2$ and $n\lambda$. This standing wave pattern results in an infinite number of paths of maximum and minimum signal intensity. If these paths were wires immersed in air this theory would be valid. These phenomena occur for wires in air because of reflection of the outgoing wave at the shorted end

[1] King, R. W. P., *Electromagnetic Engineering*, vol. 1, page 267, McGraw-Hill (1945).

of the transmission line (i.e., at the midpoint of each wire path) due to the contrast between the electrical properties of air and metal. In the homogeneous earth no contrast exists at the midpoint of the path and there can be no reflection, hence no standing waves.

In the Atlantic experiment, in order for there to be a standing wave pattern in the shale (i.e., points of maximum and minimum signal intensity) either two or more coherent sources would be required, or the single source must be longer than half a wavelength, or else the shale must be discontinuous, resulting in reflections. The first two conditions obviously are not true. The lateral extent of the shale is quite great. At several hole separation distances signal measurements were made at vertical distances from the interface between shale and lime ranging from the interface and above to more than 20 feet below. Using depth variations of only 2 feet did not show any disturbing standing wave pattern.

The theory of the response of conducting media to electromagnetic waves is well covered in the literature[1,2] and was substantiated by a preliminary experiment.

An insulated antenna, 33 inches long, was immersed in a 3.43 ohm-meter salt solution. It was connected by a short co-axial cable to a radio frequency impedance bridge. After making corrections for the connecting cable the antenna was found to have zero reactance at a frequency of 10 mc compared to a calculated frequency of 12 mc in water or 180 mc in air.

It is definitely not correct to include currents in the medium in finding the field at points in the medium if insulated antenna are used.[3]

All of the Atlantic data were taken at distances such that, theoretically, the A/d term was dominant or nearly so compared to B/d^2 and C/d^3 terms. Phase variations along the antennas could only result in small errors incapable of materially affecting the interpretation.

If, for the sake of argument, it is assumed that our measurements were taken only in a region such that the A/d term is not dominant, it would be difficult to determine an exact value for the attenuation constant, but a definite lower limit for the attenuation constant, based upon a divergence factor of $1/d^3$, is obtainable. As pointed out in the paper, this lower limit was found to be far too large to allow significant penetration through shale.

We note that Mr. Morriss repeatedly refers to a "complex" intermediate zone between 0.1 and 10 wavelengths from the antenna where "field strength calculations are not so simple." This lack of simplicity merely means that a single term of the form given by Mr. Morriss, $V = Ke^{-\alpha d}/d^n$, is not adequate to describe the situation. The general equation, given in the paper, does give the field strength at any distance from the antenna.

The Atlantic experiment was designed to eliminate certain questionable features of previous experiments. These involve the presence of interfaces between media of widely different properties which may give rise to reflections and/or air coupling between the receiver and the transmitter. These questionable features were present in the United Gas experiment.

The field equations, which are complex in a homogeneous medium, become quite difficult and involved when working close to an interface between two media.

If the soil resistivity were rather high (no resistivity measurements were made), the results would not be at great odds with conventional theory even if the experimenter's interpretation were generally accepted.

In conclusion, it is believed that the Atlantic experiment gives conclusive proof that a 1,652 kc radio wave cannot be used to penetrate many hundreds of feet of shale.

DISCUSSION

LE ROY SCHARON:* After reviewing Mr. Pritchett's paper, listening to the discussions, and from my own personal knowledge, I feel that the experiments as here presented are inconclusive. It is

[1] Bronwell and Beam, "Theory and Application of Microwaves," pp. 268–271, 402–407.

[2] Ramo and Whinnery, "Fields and Waves in Modern Radio," pp. 270–273, 429–434.

[3] King, "Electromagnetic Engineering," pp. 229, 255.

* Assoc. Professor, Washington University, St. Louis, Mo.

impossible, on the basis of his tests, to conclude that radio waves do not penetrate deep enough into the earth to be useful in prospecting.

Mr. Pritchett has already been informed that his experiments were not carried out far enough, that is to include not only the near zone but also the intermediate and far zones of the attenuation curve. His reply was that he would have to be presented with a very good reason before even taking the time to do so.

I might say that from a practical point of view I have very specific knowledge of two areas where the intermediate and far zones of the attenuated curve were important in determining the depths and outlines of two ore bodies. The first example has already been brought to your attention where a lead ore body was interpreted at a depth of 900 feet. This body was known from drilling, but its depth was not revealed to the geophysicist performing the field work. This particular application served as a means of increasing the development of the particular ore body. Incidentally, the depth of this ore body was interpreted from the intermediate and far zones of the frequency curve. The other example is of a disseminated lead ore body at a depth of 300 feet situated in a limestone very close to a sandstone-igneous contact. Overlying the limestone is a very irregular residuum varying from 0 to 200 feet in thickness. On the basis of exploration by radio waves the ore body, already known by drilling, was actually outlined with subsequent drilling proving that the new outline of the ore body as defined by radio wave technique was more accurate than the previous outline based on wide space drilling. Again these interpretations were confined to the intermediate and far zones of the frequency curve. In both cases the near zone, that zone in which Mr. Pritchett confined his tests and has drawn his conclusions, was not even used in the interpretations. I hope these examples will serve as a reason for Mr. Pritchett to continue his work beyond the scope as he has now presented it.

Needless to say I am very interested in having the full answer to the problem and the explanations why the anomalies measured can be used to interpret geologic conditions. But being a geophysically trained geologist I am interested, through necessity, in the practical applications of geophysical methods. If I can demonstrate through the application of the radio wave method of exploration to materially increase the ore reserves at any particular mine I am not compelled to justify the method scientifically before I shall be allowed to continue its use. I am sure oil companies work the same way, however it does not seem apparent from the discussions of today. Is the geologist with his knowledge of the rocks, completely ignored in the seeking of a scientific justification of new methods of exploration?

Does something have to be proven scientifically sound on the basis of our present physical concepts before allowing its practical use? Could it not be true that our concepts of the behavior of electromagnetic waves in the earth are wrong? In fact, what are our concepts? Often physical concepts have been changed and by so doing a whole new avenue of research and advancement has been opened up. The electrical resistivity method of exploration, for example, is used today and accepted as a positive geophysical method but there are those who still claim an electrical current cannot penetrate sufficiently into the earth to be practical.

Here is one concluding point. To my surprise considerable dogmatism has been expressed. Dogmatic statements have been made by various persons that radio waves *cannot* penetrate into the earth, therefore there is no basis for the application. Surely the author and the others so expressing themselves cannot completely overlook the work of Joyce, Silverman and Sheffet, Volker Frisch of Germany, the Ohio State University, the Illinois Geological Survey and others. It has already been shown that (1) the data produced in Mr. Pritchett's experiments can give entirely different results when approached in a different manner, (2) that the experiment could not be fully reproduced by others, and (3) practical applications demonstrate that there is a relationship between the physical results measured and the geology obtaining in any particular area. With these facts how can we truthfully assume such dogmatic attitudes.

Mr. Alcock in his "Isochron Analysis of Seismic Data" has given us the proper approach to the problem. He stated that the method worked and that there was a correlation between the isochrons and an actual oil field. As a physicist, however, he would attempt to prove the condition quantitatively while in the meantime the applied geophysicists will continue to use the method qualitatively. Certainly this is a positive and open mind approach to the problem.

This discussion has been a very stimulating and challenging one to the group. We should resolve with positive and open minds to seek the basic answer and to explain that if a radio wave *cannot* penetrate sufficiently into the ground then *why* can the physical anomalies or phenomena produced in these measurements be correlated with geological conditions that exist beneath the surface of the earth.

AUTHOR'S REPLY TO DISCUSSION OFFERED BY LE ROY SCHARON

Again much field data giving pro and con versions of radio wave propagation in the earth is available. The complexities and unknown quantities in these experiments, coupled with their conflict in conclusions, made it evident that a simpler, more basic experiment should be performed. This was done.

Mr. Scharon's cases might fall into either of two common categories:

I. High earth resistivity resulting in considerable theoretical penetration of radio waves.

II. Correlation of surface data with a shallow body which itself is correlatable with the deeper body of interest.

If radio frequency prospecting can determine the presence or absence of oil at great depths then it will be helpful to realize that some shallow anomaly is responsible. It has not been contended that radio waves cannot penetrate hundreds or even thousands of feet of dry, highly resistive earth.

The experiments of Silverman and Sheffet, and of Joyce, confirm rather than deny conventional theory. Most published data purporting to show low attenuation in conducting media are open to criticism due to ambiguity of path between transmitter and receiver. We consider that the data we have presented, conclusively show that the attenuation is very great, and that our experiment has not been properly reproduced by others.

DISCUSSION

GLENN J. BAKER:* Pritchett's measurements were made so near the transmitting antenna that it is doubtful if the simple radiation formula (Equation 3) properly represents the data. His equation (3) implies that measurements are to be made at distances large compared with the physical size of the antenna structure and at distances great enough for the radiation field only to be significant. A graph is presented herewith (Fig. 1) to show how erroneous values of the attenuation factor can be obtained when Equation (3) is applied in the region near the transmitter.

The graph shows results obtained at a frequency of 1,700 kilocycles in air over the ground. These data were obtained recently in the course of a mining survey in the lead and zinc district of Northwestern Illinois. The observations are shown in the same way as in Pritchett's Figure 11, where the receiver output times the distance between the receiver and transmitter is plotted on a logarithmic scale against the distance from the receiver to the transmitter on a linear scale. In both his figure and the writer's, the assumption is made that the simple radiation formula will be a sufficiently close approximation. Observations were taken less than one wave length from the transmitter.

It is obvious that the slope of the graph is not constant. If one observer obtained data only over the range covered by the first part of the receiver traverse (104 to 115 feet), he would conclude that the attenuation factor is 0.14 nepers/ft. If another observer worked only over the range represented by the right-hand portion of the graph (210–264 feet), he would find an attenuation factor of 0.0044 nepers/ft. Actually, of course, neither of these values is correct. The attenuation of radio waves through air over ground is much smaller. Values obtained from field observations, and from the literature, such as Norton's papers,[1] are of the order of magnitude of a number with four zeros between the decimal point and the first digit.

* Wm. M. Barret, Inc., Shreveport.

[1] K. A. Norton, "Propagation of Radio Waves Over the Surface of the Earth and in the Upper Atmosphere," *Proc. Inst. Radio Eng.*, *24*, 1307–1367 (October 1936); and *25*, 1203–1236 (September 1937).

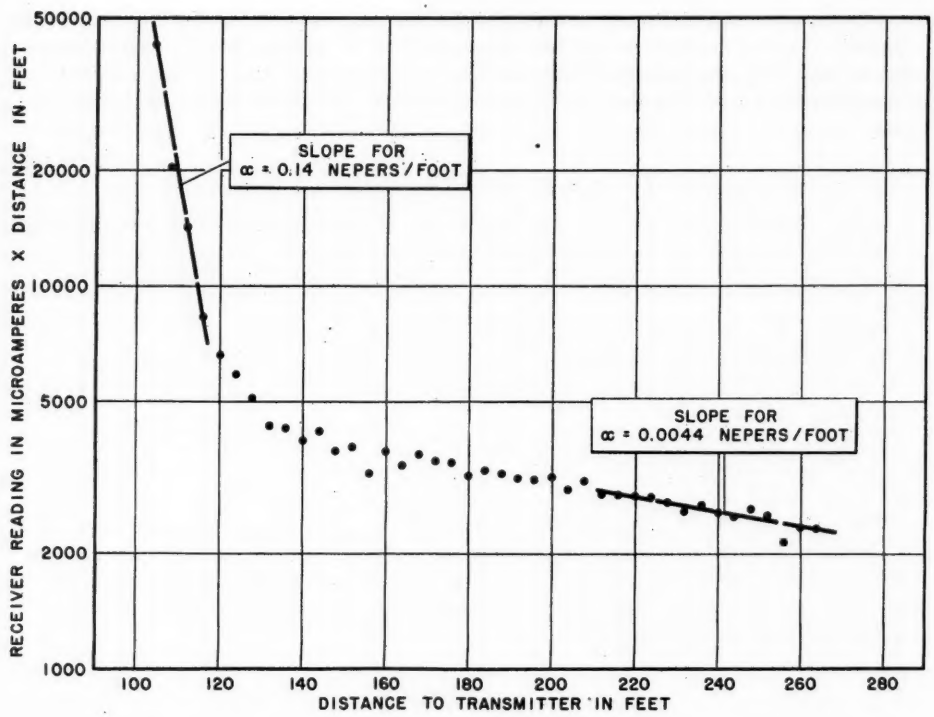

FIG. 1. Receiver output times distance to transmitter versus distance. These data illustrate how variable and erroneous values of attenuation factor result when Equation 3 is applied within a wave length of the transmitter.

Thus the far-field radiation formula fails as a useful approximation in the neighborhood of the transmitter. Consequently, correct values for attenuation factors can not be obtained by its use under such conditions.

Morriss and McGehee have calculated a wave length of about 27 feet in the shale from Pritchett's data. Hence, on the basis of their calculation, most of Pritchett's data were obtained within one wave length of the transmitter. As indicated in the preceding paragraphs, the application of the far-field radiation equation at such short distances leads to a value for the attenuation factor that is much too large. Accordingly, if Pritchett's value for the attenuation factor were reduced, then recalculation would show a still larger value for the wave length, and consequently the observation sites would have been even closer to the transmitter in terms of wave length.

The free-space length divided by the calculated wave length in the shale gives a ratio of about 22 to 1. There are reasons for believing that such a large reduction in wave length is abnormal and not characteristic of shale.

To cite one example, some years ago William M. Barret, Inc., obtained data on the wave length in the Midway formation of Northwestern Louisiana by another method. The ratio of free-space wave length to wave length in the Midway came out to be 2.32 to 1. The Midway formation in this area is nearly all shale; it is approximatelv 700 feet thick and is about 500 feet deep. The method used is described in detail in U. S. Patents *Nos. 2,426,918* and *2,573,682*.

The significance of the wave-length ratio, which is another expression for the index of refraction, is that there is a functional relation between it and the attenuation factor α. If the wave-length ratio is small, then the attenuation factor can not be large.

Inasmuch as Pritchett's value for the attenuation factor was determined by application of the far-field radiation equation in the near neighborhood of the transmitting antenna, and since the result so obtained appears to be in disagreement with the findings of others, it is highly probable that the value cited by him for the attenuation factor of shale is far too large.

AUTHOR'S REPLY TO DISCUSSION OFFERED BY GLENN J. BAKER

Haycock, Madsen, and Hurst (reference 2, p. 207) obtained an experimental ratio of 10 for the wave length in air relative to the wave length in slightly damp sandy soil (resistivity not measured) at broadcast frequencies. This would check the Atlantic ratio if their soil resistivity were about four times as large as the low resistivity shale used in the Atlantic Experiment.

This, as Mr. Baker points out, is further proof that high attenuation of radio waves is to be expected in damp earth.

DISCUSSION

WM. M. BARRET:* Pritchett's experiment is open to the severe criticism that it was conducted on far too small a scale to produce authentic results.

The unfortunate choice of scale apparently was dictated by the apparatus employed, which was capable of communicating but a comparatively weak radio signal through 155 feet of air. And when the apparatus was immersed in columns of salted mud, the possible range of communication within the earth was so reduced that it became necessary to operate the receiver within some 30 feet of the transmitter.

This placed the receiver at all times within the complex portion of the electromagnetic field in the near neighborhood of the transmitting antenna. It is well-known that this region, which may be defined as the "near field," is made up of the electrostatic field, which falls off as the inverse cube of the distance; the induction field, which declines as the inverse square of the distance, and the radiation field, which varies as the inverse first power of the distance.

Radio engineers will not attempt to make measurements of the radiation field within this complicated region, but confine their measurements to the "far field," which begins some five to 10 wave lengths from the transmitting antenna.

But contrary to this establshed practice, Pritchett did operate his receiver within the near field, taking readings from 5.4 feet to 33.2 feet from the transmitter.

Now he acknowledged the complexity of the near field and devoted a page in his paper to an equation which presumably defines in rigorous terms the voltage input at the receiver for various separations of the transmitting and receiving antennas. But, he said that this equation was too cumbersome to use.

So, as a first approximation, he assumed that his six-foot transmitting antenna was a point source of radiation and that his six-foot receiving antenna was a point of reception. This assumption would be permissible had he operated his receiver at distances that were great in comparison with the length of the antennas, but to say that his minimum distance of 5.4 feet is great in comparison with antennas measuring six feet in length, or to say that the six-foot antennas may be regarded as points when the maximum separation of the antennas was but 33.2 feet, is simply to disregard completely the basic geometry of the experiment.

Furthermore, as a second approximation, Pritchett also assumed that he could ignore the electrostatic and induction fields, which predominate within much of the near field, and that he could attribute the receiver readings entirely to the effect of the radiation field. The validity of this assumption is denied by the rapid decline of the receiver readings, which is characteristic of the similarly rapid decay of the electrostatic and induction fields, and by the scattering of the observed readings, which may well be indicative of interference effects within the near field.

He then pointed out that he justified the use of his second approximation by finding that it checked satisfactorily with the first approximation, but he leaves one completely in doubt as to how

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either of these untenable approximations would check with his Equation (1), which is presumed to be a rigorous expression based on the actual antenna structures and on the undisputed presence of the electrostatic and induction fields.

The stated purpose of Pritchett's experiment was to determine the attenuation by experimental results beyond question in value or interpretation.

This commendable purpose was defeated by the miniature scale of the experiment.

AUTHOR'S REPLY TO DISCUSSION OFFERED BY WM. M. BARRET

Mr. Barret objects to our immersion of the instruments into columns of salted mud yet the conductivity of the salted mud was no greater than that of the shale. In addition, since the length of path through mud was only a few inches at most, this objection is unwarranted.

Radio engineers could make measurements of attenuation in the middle zone with respect to a transmitter in air. Interpretation would be somewhat more difficult and results not extremely accurate. In the Atlantic experiment, accuracy within an order of magnitude would be quite sufficient.

The signal intensity at each distance would be actually somewhat smaller than that given by the simple Equation (3) due to the considerable length of the antenna compared to the separation distance. This error would be larger at 5 feet than at 30 feet, which would give too small a value for the experimental attenuation constant. A rough numerical integration of Equation (1) over the two antennas shows that this error is not large.

As shown in Figure 10 the theoretical change in slope of the signal decline curve when induction and electrostatic fields are included is minor for resistivities of 18 ohms and less in the range of distances used.

Even if this were not true, the least possible value of the attenuation constant would result assuming a divergence factor of $1/d^3$. This value of the attenuation constant is still very large.

DISCUSSION

CHARLES W. SHANNON:* This discussion is confined to observations on the use of radio frequency waves for sulphide ore exploration. One theoretical consideration which should be pointed out is that Mr. Pritchett's experiment was carried out in the "near zone," whereas the following investigations deal with waves in the "far zone."

A technique developed by the William M. Barret Corporation has been employed for the past eighteen months. Fundamentally, the process consists of transmitting rf energy through the earth and measuring the unattenuated fraction returned from the sub-surface. Where the various rock strata are of uniform lithology and no sharply differing dielectric facies exist, the energy dissipation varies inversely with the distance from the transmitter, so energy received plotted against distance produces a smooth curve. However, a sulphide ore body apparently gives rise to a phenomenon which introduces additive energy to the measured field, and a plot of such values results in an anomalous curve marking the presence of the sulphide body.

In our experimental work it was found that anomalous profiles could be reproduced persistently, proving that whatever the cause of the anomaly, it was a fixed phenomenon. It thus lends itself to plausible interpretation.

Experimental work was conducted in areas where geological conditions were well known, and no ore body ever failed to produce an anomalous curve.

Following are the results of surveys made in unexplored areas:

1. An area of dolomite with some intercalated beds of shale in which mineralization occurs at a depth of 600 to 900 feet was explored for possible extensions of an ore body. Results outlined the extensions of the trend and showed another zone on an opposite flank of the structure. Diamond core drilling confirmed results in both cases.

* St. Joseph Lead Co., Bonne Terre, Missouri.

2. An area of dolomite explored for mineral 400 to 500 feet deep produced no indicative anomalous curves, and check diamond core drilling confirmed the absence of mineralization.
3. An area of dolomite with expected depths of possible mineral of 200–400 feet produced low order anomalies interpreted as indicative of weak mineralization. Diamond core drilling showed sub-commercial mineral scattered through the area.

Not all tests made, however, produced conclusive results. The variables inherent in any geophysical procedure make interpretation subject to error, and the results of practical field work do not always coincide with the theoretical concepts. That is the point of this discussion; that the conclusions drawn by Mr. Pritchett do not with finality preclude the use of radio frequency waves for investigation of subsurface geology. It is felt that the above field application does offer proof that attenuation is not too great to prevent penetration of radio waves into the sub-surface strata.

AUTHOR'S REPLY TO DISCUSSION OFFERED BY CHARLES W. SHANNON

Volumes of empirical field data undoubtedly could be produced, some confirming and some denying the possibility of high frequency radio wave penetration in the earth. Some of the published data showing significant penetrations rather than being at odds with conventional theory actually are in agreement due to the prevailing extremely high resistivity of the earth penetrated. It is possible that the cases described fall into this category. (Dolomite is normally rather high resistivity material.) Possibly, also, these surveys mapped even shallower anomalies which themselves correlated with the ore body.

Since oil is usually associated with salt water saturated formations of low resistivity, and is generally at much greater depths than those quoted by Mr. Shannon, the applicability of radio frequencies in prospecting for oil is not made more credible.

DISCUSSION

R. D. WYCKOFF:* It would be far more profitable perhaps to repeat Pritchett's experiment exactly, except with the receiver located at a truly acceptable number of wavelengths from the transmitter—if indeed enough kilowatts can be provided to carry on the experiment.

I do not understand why numerous references in the literature are so frequently ignored when they *do* agree both with theory and Mr. Pritchett's conclusions. I recall for example an experiment by some German workers who placed a receiver in a tunnel having no metallic conductors. Overhead on the hilltop was the transmitter with several hundred feet of relatively dry earth and sandstones intervening (the watertable lying below the tunnel). And even in this rather favorable high-resistance material, the observed attenuations were such as obviously to preclude rf penetrations of some thousands of feet in any normal subsurface material.

Some have objected to Mr. Pritchett's attenuation figures on the basis that perhaps they fortuitously represent the false attenuation arising from observing a portion of an interference pattern, i.e., a standing wave pattern such as you apparently observed in your ditch-antenna experiments. It is beyond my comprehension how, in a system involving a single dipole source completely surrounded by highly attenuating material only, such a presumed standing-wave pattern might be initiated.

* Gulf Research and Development Company, Pittsburgh.

RELATION OF SEISMIC CORRECTIONS TO SURFACE GEOLOGY*

H. M. THRALLS† AND R. W. MOSSMAN†

ABSTRACT

The arbitrary application of any set type of near-surface corrections to seismic data can lead to erroneous results. The determination of the type of correction to be used must be based, in part, on the type of formations present in the near-surface. Case studies are offered to illustrate conditions arising in areas of youthful and mature topography. Specifically, they deal with a complex low velocity layer problem in a river valley, a pre-glacial topography in the Illinois Basin, a problem arising in a mature topography in Kansas, and a youthful topography in central Wyoming. In such cases, the use of a "floating" elevation reference plane is advocated for the "Correction Zone" lying immediately below the surface.

The accuracy of seismic investigations is conditioned by many variables which are an integral part of the area being explored. Of these, the two factors most seriously affecting the interpretation, assuming valid recording of the data, are subsurface velocities and near-surface corrections. The latter subjects the time data to local variations of much greater magnitude and of more erratic nature than subsurface velocity variation. Many so-called subsurface velocity gradients are, to a large extent, correction gradients which compensate for failure to properly correct the recorded time data before the well ties are evaluated.

The geologic section in which these near-surface variables occur ranges from the surface at the highest elevation encountered on the prospect downward to the deepest point at which a stratum of unweathered and well consolidated material is encountered. This zone includes the recognized geologic zone of weathering and the more or less equivalent seismic low-velocity layer, as well as some additional unweathered section associated with the topographic relief. The lower limit of this zone is not necessarily a plane parallel to sea level, and may or may not be related to any identifiable formational interface. The term "Correction Zone" is suggested here as descriptive of this section and is so used in this paper.

An investigation of the topographic conditions present in any prospect area, together with surface outcrops, will furnish the experienced seismologist with general ideas as to the correction problems to be encountered. In evaluating topography, division can be made into two fundamental classifications: youthful and mature. All topography represents expression of varying combinations of the two and can be described in terms of stage of maturity.

Figure 1 represents an idealized cross section of an area of youthful topography. Youthful topography is characterized by active vertical erosion. Land-

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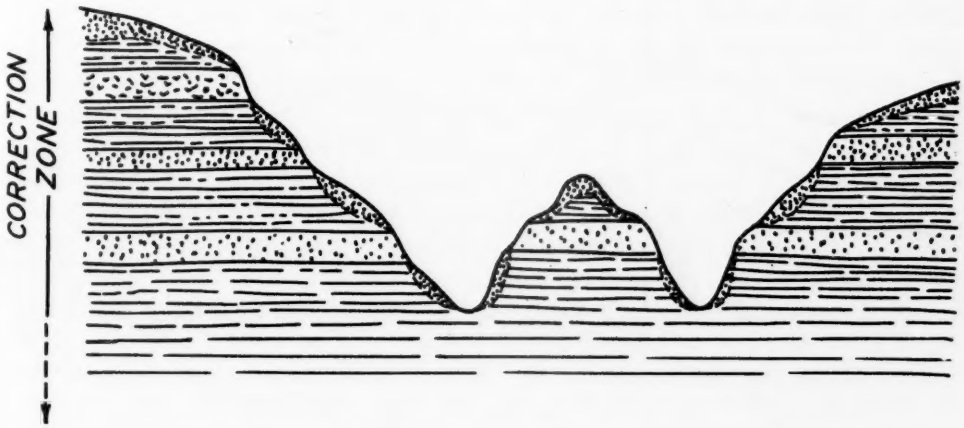

FIG. 1. Generalized cross-section illustrating youthful topography.

forms typical of youthful topography include primarily mountain areas and plateaus.

Mature topography is illustrated in Figure 2. It is characterized by lateral erosion and aggradation and is normally represented by low, rolling terrain with broad river valleys. In the northern part of the United States and in Canada continental glaciation is often present in such areas.

It is in areas of mature topography that the largest variety of correction problems are encountered. The surface usually furnishes no positive indication of the variations in the near-surface materials, their velocities, or their thicknesses. It is necessary in such areas to rely entirely on information obtained through the seismic program, either directly by means of shot hole logs or indirectly from recorded time data.

Among the most complex correction areas are those in which a mature topography has been elevated or rejuvenated, in which case a combination of the problems of both mature and youthful areas may be present.

The accuracy of any seismic survey is dependent primarily on the accuracy of the corrections used. The most common approach to the correction problem is

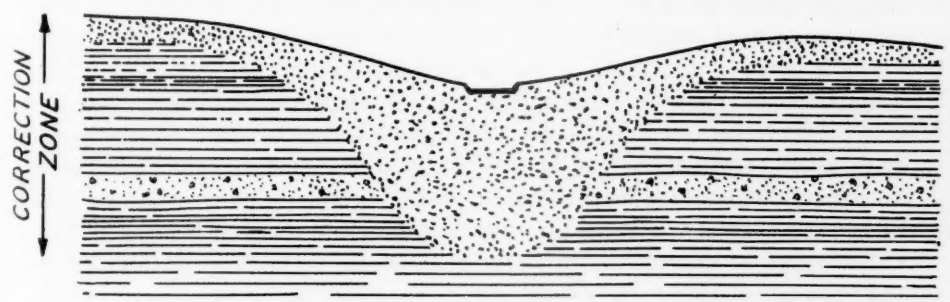

FIG. 2. Generalized cross-section illustrating mature topography.

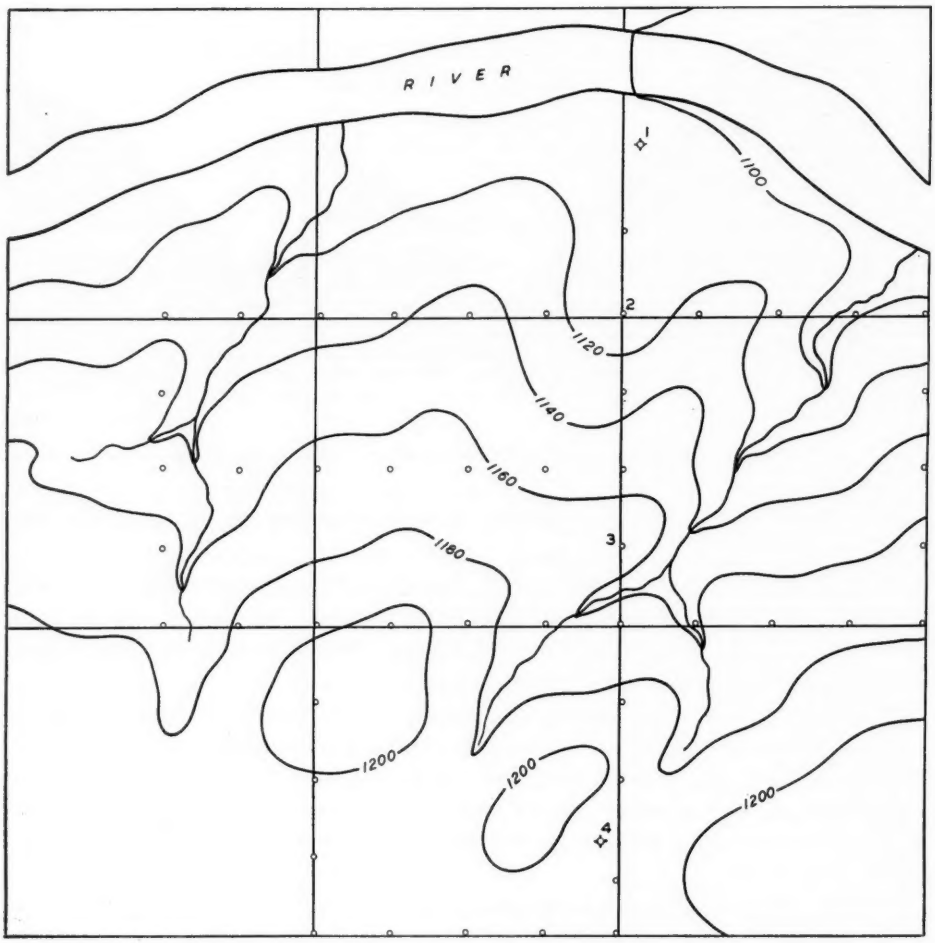

FIG. 3. General topography and shooting plan of a small seismic prospect located in Southern Kansas.

through the use of the so-called normal uphole method in which the shot is presumed to have been fired at or below the base of the velocity layer and the uphole time is taken as a measure of the travel time through that section above the level of the shot. Elevation corrections may be calculated to reduce the time data to a horizontal reference plane. This uphole correction method yields generally excellent results if the shot is fired below all near-surface velocity variables in the correction zone and if no change in these variables is present laterally between the seismometer positions used for time data and the shot hole.

Other types of corrections in fairly general use include: variations of the curved path weathering methods which presume a continuous increase of velocity with depth, methods based on the assumption of refracted time travel along a

particular velocity interface, and modifications of the uphole correction method.

All of these correction methods are reasonably reliable when applied in areas in which the basic assumptions embodied in the method coincide with the physical conditions actually presented in the area. None can be applied indiscriminately as a universal correction method, since variations in the make up of the correction zone require variations in correction technique.

A decision made in the early stages of a survey as to the problems of an area can lead to improper interpretations if the interpreter is not continually watchful for changing conditions. Such a situation occurred in a small seismic prospect showing mature topography and a complex correction zone which was conducted in southern Kansas along the Arkansas River. Two dry holes were present in the area, fortuitously located so as to provide a measure of accuracy of the seismic data at the extremes of correction zone variation. The general topography of the area is shown in Figure 3. Outcrops are obscured by a mantle of Quaternary sand, and a multiple layer correction problem was anticipated. Work was started at

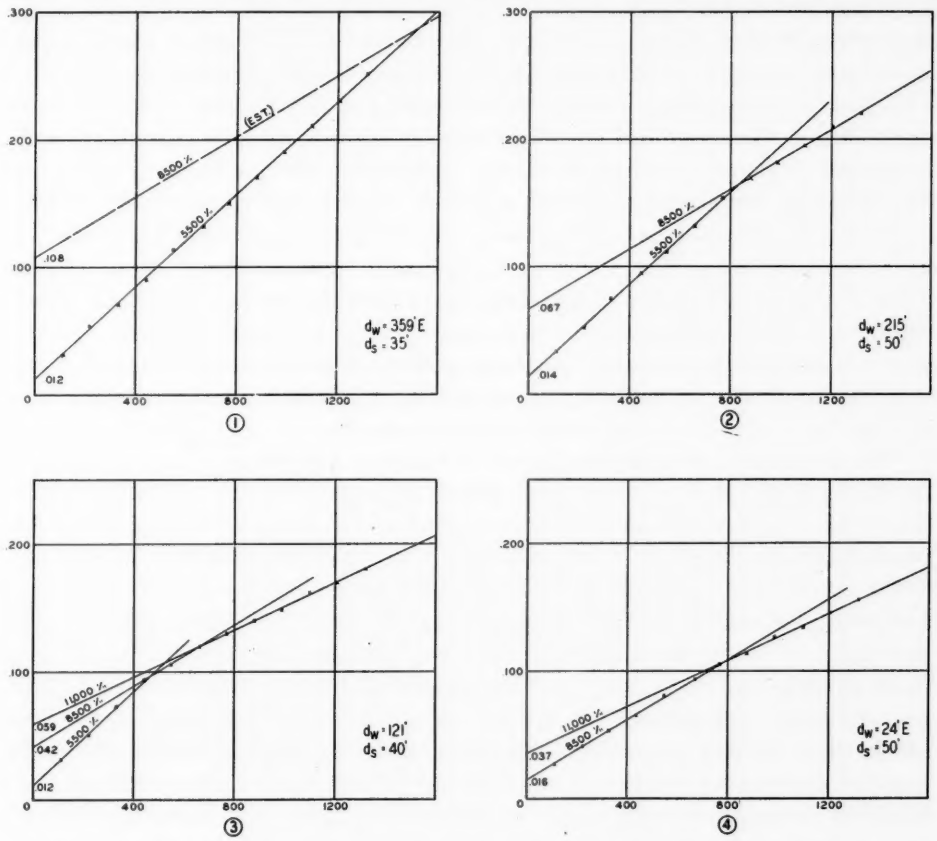

FIG. 4. Graphs of "first break" energy arrivals showing four types obtained, numbered to correspond to locations shown in Figure 3.

the No. 2 shot point location. The first time-distance graphs which were plotted from the refraction times indicated the area to be conformable with anticipated conditions and workable using a "two-layer" weathering method. Continuing on this basis, the prospect was completed in a few days' time and the crew moved from the area before the final interpretation was made. The seismic data obtained from this interpretation radically failed to check the depth data shown by the dry holes, actually showing dip in a reverse direction. The record quality was generally good and no errors in continuity or correlation could be found. The reflection troughs picked at each well were quite definitely correlative.

A review of the "first break" graphs was made and detailed analysis thereof revealed, instead of one type of two-layer condition, four distinct variations. Figure 4 illustrates the four general types encountered. The examples are numbered to correspond with the positions identified in Figure 3. The graph shown as Type 2 is typical of those encountered by the initial work on the prospect, and shows simple two-layer conditions with velocities of 5,500 feet per second and 8,500 feet per second. Type 1 graph is characteristic of those ecountered adjacent to the river at the dry hole near Shot Point No. 1. Only a 5,500-foot per second slope can be positively identified. The 8,500-foot per second base of weathered layer velocity shown by the original work can not be identified, and it is assumed that the horizontal spread distance of one-quarter mile was insufficient to permit recording of refracted energy penetrating to this layer. In the area farther south, graphs similar to that shown as Type 3 were encountered. In this instance the 5,500-foot per second slope was recorded, apparently underlain by an 11,000-foot per second velocity. More careful examination of these graphs shows that a 8,500-foot per second slope exists between the juncture of the other two lines but is so obscured as to have been disregarded in the original interpretation. A fourth type of graph was encountered which shows velocities of 8,500 feet per second and 11,000 feet per second. No 5,500-foot per second slope was obtained.

The theoretical cross section shown in Figure 5 was prepared on the basis of the information obtained from these graphs and illustrates the probable conditions which they represent. At the north end of the prospect the depth of the Quaternary sand, having an interval velocity of 5,500 feet per second, is in excess of the maximum theoretical distance at which return energy could be obtained with one-quarter mile surface coverage. Near the location of Shot Point No. 2, this sand was of less depth and refraction was obtained through the underlying shale which has a velocity of 8,500 feet per second. Farther south at location No. 3 a high-speed (11,000-foot per second) sandstone layer was postulated, lying within the 8,500 foot per second shale. This sandstone member offered a suitable mode of transfer for the energy to the more distant seismometer positions. Adjacent to the southern well, located at position No. 4, the shot holes were drilled to sufficient depth to penetrate through the Quaternary sand into the underlying shale. The deeper sandstone layer furnished a second slope, and the graphs have

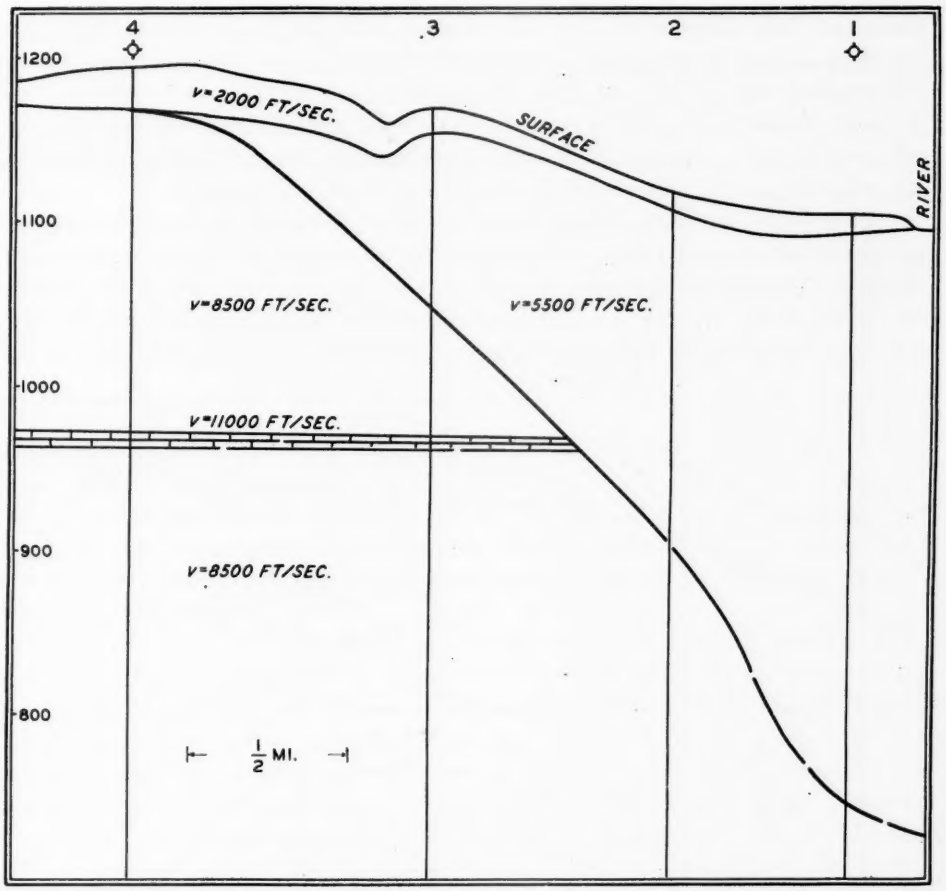

FIG. 5. Cross-section showing near-surface conditions in area shown in Figure 3, as interpreted from seismic data.

the appearance of normal two-layer conditions, but with velocities which are abnormal for the area.

Having established a hypothesis of the physical conditions existing in the correction zone on this prospect, the correction values were recomputed. A map was prepared showing the elevation of the base of the Quaternary sand zone, as shown in Figure 6. North of the dotted line adjacent to Position No. 2, the base of the sand was extrapolated to the dry hole, using a value there which would provide a correction suitable to tying the well data. Subsequent shooting at a later date, using half-mile spreads, confirmed the accuracy of this extrapolation.

An example of another type of correction zone problem is shown in Figure 7. This simplified cross section represents part of a seismic traverse conducted in the Illinois or Interior Coal Basin. This area, like most of the north-central United States, presents a mature topography which has been subjected to continental

glaciation. The Correction Zone is composed of a pre-glacial topography with concomitant weathering covered by a blanket of glacial drift having its own independent topographic features. In general, most of the rivers, such as the Wabash, follow the same course today as in pre-glacial times. Others, like the Mississippi, have changed their course considerably, the pre-glacial Mississippi River having had a course well to the east of its present position.

In the particular instance illustrated by Figure 7, the phenomena encountered were generally expected and no major difficulty of interpretation was experienced. A gravity maximum had been mapped in the area and was one of the factors which led to selecting the prospect for investigation. As determined from the shot hole logs, uphole times in the shot holes, and refraction information, the low-ve-

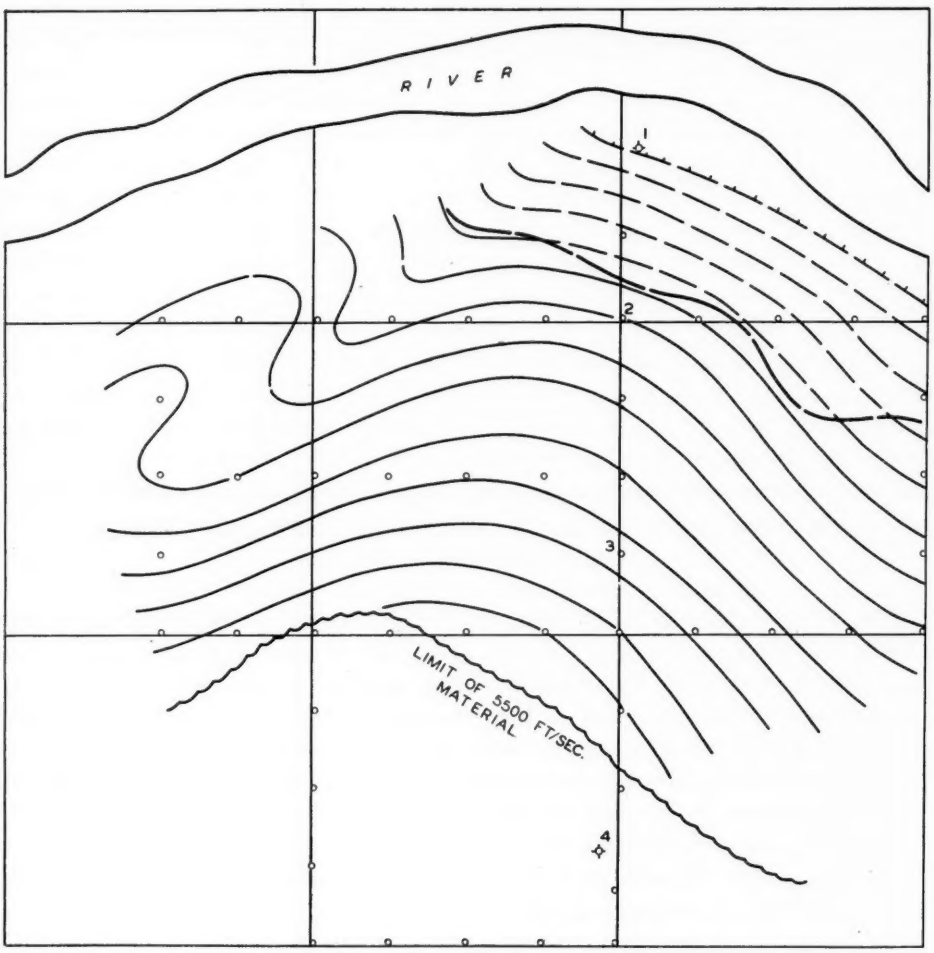

FIG. 6. Elevation of base of Quaternary sand in seismic area shown in Figure 3. Contours extrapolated north of dashed line.

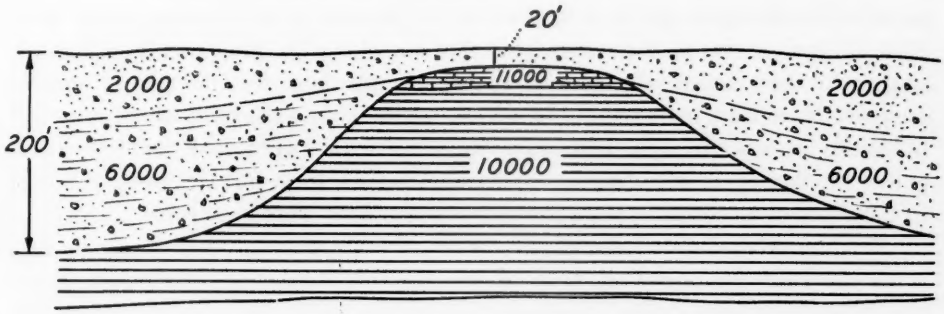

FIG. 7. Cross-section showing "Correction Zone" along part of a seismic traverse in the Illinois Coal Basin.

locity layer varied from a thickness of approximately 200 feet at either side of the buried ridge to approximately 20 feet at the crest. A hard crystalline limestone was encountered at depths of 18 to 30 feet in the shot holes located on the ridge. The gravity anomaly was thus explained by these irregularities in the correction zone since no deep seated structure was disclosed by the seismic data after proper corrections were applied.

While working a seismic prospect in Stafford County, Kansas, a condition was encountered which was thought to be similar, physically, to the Illinois situation, although no glacial drift was present. Figure 8 shows a simplified cross section of the correction zone in this area. Refracted "first break" energy from a considerable portion of the area disclosed typical two-layer weathering conditions, consisting of 5,500- and 8,500-foot per second velocity materials. In another portion of the area a bed was indicated at shallow depth having a velocity of 11,000 feet per second. In the transition zone between these two velocity areas, both 11,000- and 8,500-foot per second velocities were recorded, although the 11,000-foot per second energy largely masked the impulses from the slower material. However, in this transition zone the 11,000-foot per second energy was attenuated so rapidly with horizontal distance that the 8,500-foot per second energy was

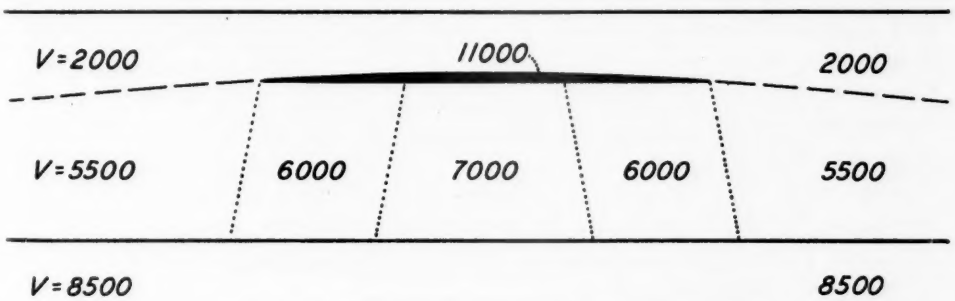

FIG. 8. Cross-section showing "Correction Zone" encountered on prospect in Stafford County, Kansas.

recorded by the more distant seismometers of the quarter-mile spread being used. First analysis of this problem suggested that a buried ridge had been encountered, similar to that shown in Figure 7. Before the prospect was completed several deep dry holes were included in the seismic traverse, and the data were found not to tie the reported tops in these tests. Relative ties between wells located within one of the two types of correction zones were satisfactory, but ties from one zone to the other or to control points in the transition zone were unreliable.

Because of the limited size of the survey, the problem imposed by the failure to tie the wells was only fully realized near the termination of the project. A few deep shot holes were drilled in an effort to obtain additional information on the physical conditions prevailing in the correction zone, although an insufficient number of holes were secured to furnish a positive answer. The high velocity material was found to be of limited thickness and shale was encountered underneath. A sample of this high velocity material was obtained, and a thin section made at the University of Tulsa. The material was described as being the result of secondary mineralization with crystalline calcite cementing quartzite grains.

Uphole times obtained in these shot holes indicated velocities of approximately 6,000 feet per second in the transition zone near the edge of the stringer and 7,000 to 7,500 feet per second in the zones where the high velocity "stringer breaks" were dominant.

The data obtained from both uphole time analyses and refraction time plots suggested that the velocity in the material below the stringer varied laterally from 5,500 feet per second where no stringer material was present to as high as 7,500 feet per second under the main body of the stringer. The information available on the prospect was insufficient to delineate the areal limits of these zones, thus permitting computation of accurate corrections with correspondingly accurate depth maps. Therefore, the isopachous maps showing intervals between reflection horizons, which were not affected by correction variations, were considered the best guides to structure in the area.

The illustrations presented above are all taken from areas of mature topography in which multiple layer problems were encountered. In areas of youthful topography the near-surface low velocity layer is often comparatively thin. In such instances, the shots normally are placed below the weathered layer and the uphole time serves as an adequate measure of travel time through that zone. Elevation variations in such areas, however, are usually extreme and the "Correction Zone" offers a distinct and unique problem for that reason. Occasionally areas are encountered in which a mature topography has been rejuvenated through uplift. In such cases a combination of correction problems may be encountered, involving both complex weathering conditions and rapid elevation variation. Parts of the Julesburg and Williston Basins may be representative of rejuvenated topography.

An area of youthful topography is illustrated by the cross section shown in Figure 9. It is generalized from actual data obtained on a prospect located in cen-

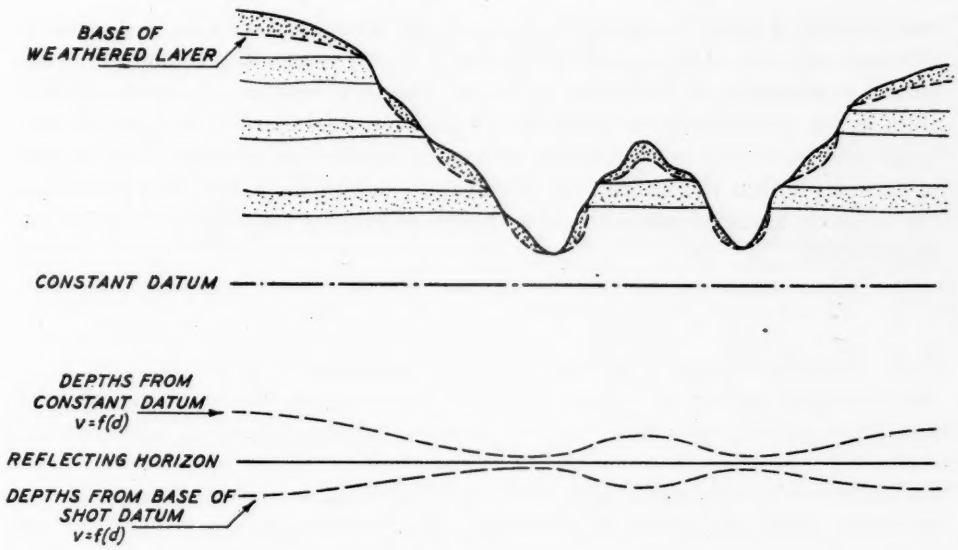

FIG. 9. Cross-section generalized from prospect in central Wyoming to show effect of topography on subsurface data.

tral Wyoming. The recorded data were first corrected to a horizontal reference plane. They showed parallelism with the surface topography as shown by the upper dashed line. Conversion to depth directly from the elevations of the shots, which were at approximately a uniform depth below the surface, resulted in apparent inversion of the topography as shown by the lower dashed line.

Several solutions might have been used to satisfy the problem posed by this failure to eliminate topographic effects and the consequent failure to tie the well data in the area. A common approach is the use of velocity variables such as a variable correction velocity or a variable average velocity based on a "velocity gradient map." In this particular instance, however, a solution was obtained by using a "floating" reference datum which was arbitrarily drawn at the approximate mean of the horizontal datum and the base-of-shot datum. This method resulted in reasonably accurate well ties, and the data obtained did not appear to be influenced by topographic relief.

Other types of "floating" elevation datums which can be used in areas of youthful or rejuvenated topography are those based on predetermined near-surface velocity combinations or on fixed relationships with the surface, either direct or functional.

Correction problems presented by the "Correction Zone" in areas of youthful topography are associated primarily with variations in the velocity constants below the recognized weathered or low-velocity layer. These variations are caused, at least in part, by variations in the surface and near-surface materials and varying amounts of over-burden above the reflecting horizon. Correction prob-

lems in areas of mature topography normally are associated with the low-velocity or weathered layer. Mature topography rejuvenated to youthful topography presents a combination of both type problems. The total number of correction variables are approximately the same as the possible combinations of geologic materials and variations in overburden. Few areas can be worked with a high degree of accuracy unless the interpreter is willing to change his calculation procedure and velocity assumptions with each change of physical conditions in the Correction Zone.

UP-HOLE TIMES*

J. P. WOODS†

ABSTRACT

The up-hole travel time for the seismic impulse from a dynamite explosion is isually taken to depend only on charge depth and formation velocity. In practice, the measured travel time is influenced by charge size, by filter setting, by instrument sensitivity, and by previous history of the shot hole. In some areas, there occur anomalous up-hole times which are difficult to explain.

Unfortunately, it is necessary to apply corrections to the reflection travel times measured by the seismograph. Unfortunate, also, is the fact that these corrections themselves are sometimes incorrect. One such correction is the up-hole time.

In Figure 1 is shown a sketch of a shot hole and of the record from which the up-hole time is determined. In seismic computation, the up-hole time is the time

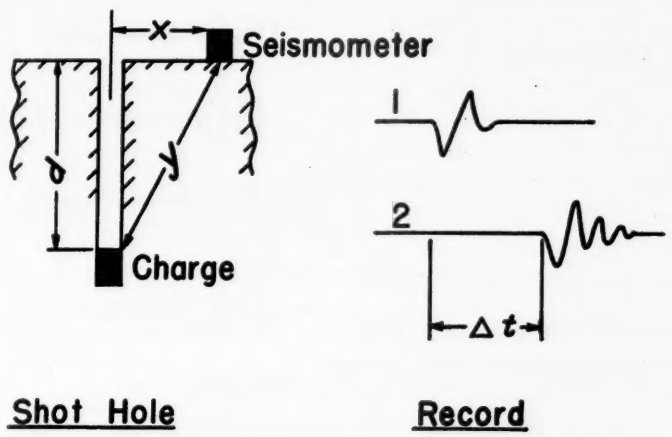

FIG. 1. Shot hole and up-hole time record.

required for seismic energy to travel vertically upward from the explosive charge to the surface of the earth. As used here, the term "up-hole time" will mean the time interval "Δt" as measured on the record from time-break to first deflection of the up-hole trace; see Figure 1. For a number of reasons, this up-hole time is only an approximation to the time required for a seismic impulse to travel the slant distance "y."

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One of these reasons is the fact that propagation of energy near the charge is not seismic propagation. Near the charge there is a region of explosion or shock, and within this region the elastic limit of the earth material is exceeded. Hence, energy is propagated not at seismic velocity $=\sqrt{\text{elastic constant/density}}$ but at some higher "shock" velocity. For a small charge, the region of explosion is small, and propagation occurs at shock velocity for only a small fraction of the travel path. But, for a large charge, the region of explosion is large, and propagation at shock velocity occurs for an appreciable fraction of the path. Hence, a

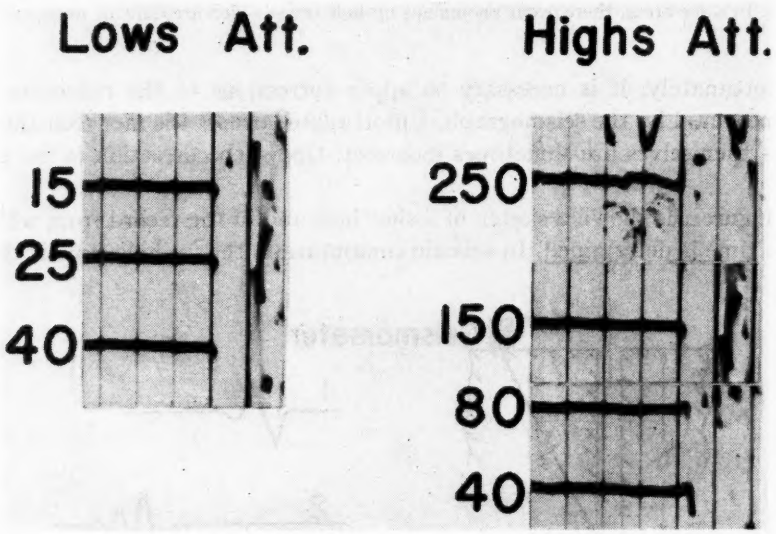

FIG. 2. Effect of filter settings.

large charge will often give an up-hole time which is 2 or 3 milli-seconds shorter than the up-hole time from a small charge.

The effects of a previous shot must be considered. The previous shot made some sort of cavity. Depending upon the character of the earth material, this cavity contains loose sand, clay, or rock. If the new charge is properly tamped, the cavity is filled with water; otherwise it may be partly filled with air. Further, the cavity is surrounded by a region of aeration—a region into which gases have been driven by the high pressure generated by the explosion. The effect of aeration is to lower seismic velocity. Usually, when a shot is repeated at the same depth, the up-hole time from the repeat shot is 1 or 2 milli-seconds long. It is impossible to shoot twice in the same place. After the first shot, the same place is not there any more.

Filter setting affects the measurement of up-hole time. In Figure 2 is shown an up-hole shot as recorded at seven different filter settings. In this figure, the time-break is not shown; since the discussion is concerned only with relative up-hole times, this is of no consequence. For the three traces on the left, the low frequen-

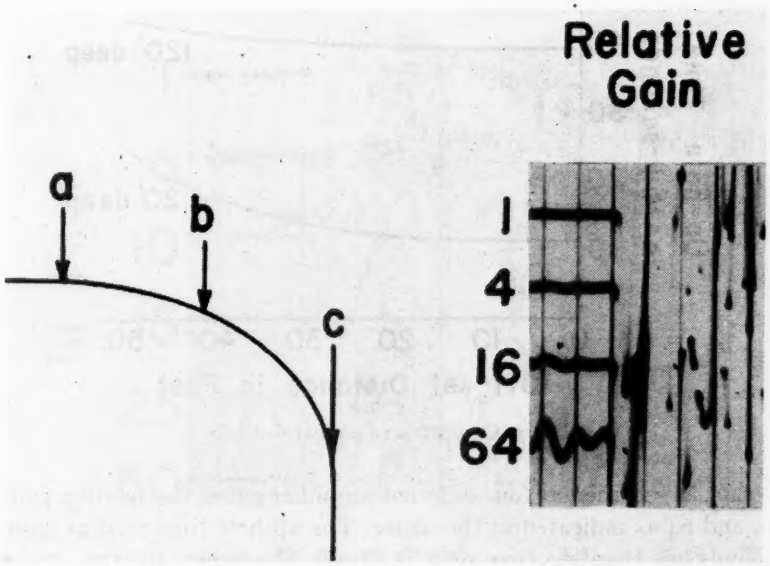

FIG. 3. Effect of sensitivity.

cies are attenuated, the attenuation starting at 15 cps for trace No. 1, 25 cps for trace No. 2, and 40 cps for trace No. 3. There is no observable effect on the up-hole time. For the four traces on the right, the high frequencies are attenuated, attenuation starting at 250 cps for trace No. 1, 150 cps for trace No. 2, 80 cps for trace No. 3, and 40 cps for trace No. 4. The up-hole time read from trace No. 4 is 3 milli-seconds longer than the up-hole time read from trace No. 1. (Note that trace No. 1 on the right is reversed; it kicks up, and the other traces kick down.)

Sensitivity also affects measurement of up-hole time. In Figure 3 is shown an

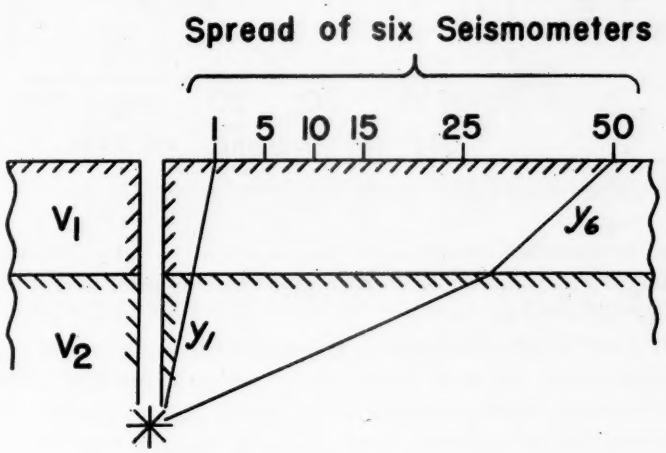

FIG. 4. Spread of up-hole seismometers.

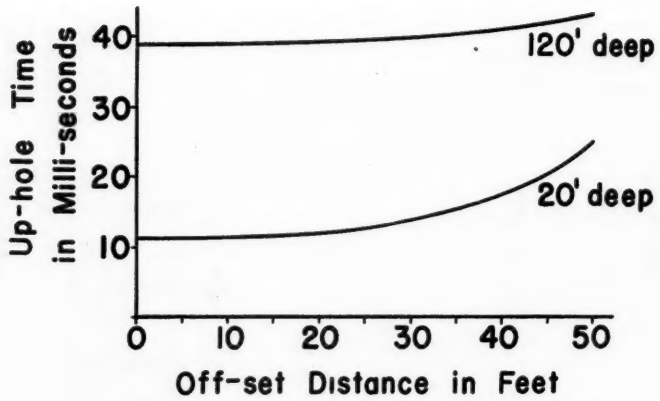

FIG. 5. Curves from a normal shot hole.

up-hole shot as recorded at four different amplifier gains, the relative gains being 1, 4, 16, and 64 as indicated in the figure. The up-hole time read at gain 64 is 2 milli-seconds less than the time read at gain 1. The reason for this apparent decrease in up-hole time with increase in gain is indicated on the left of the figure. The sketch on the left shows the deflection of the up-hole trace greatly magnified.

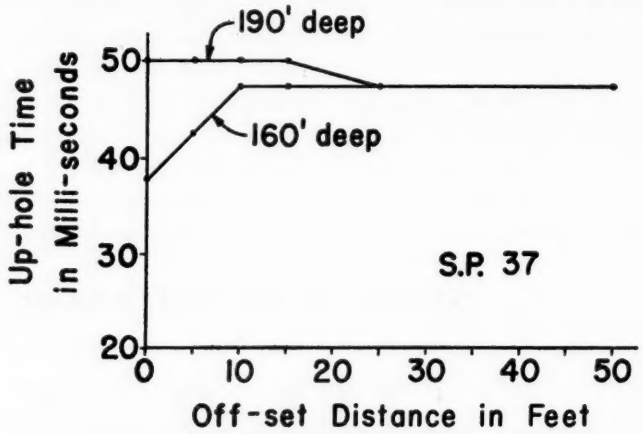

FIG. 6. Abnormal time-distance curves.

At low gain, the up-hole time would be read at point "c"; at higher gain, the time would be read at "b"; and, at still higher gain, the computer would read the start of trace deflection at point "a."

Consider now the effects of setting the up-hole seismometer at some distance from the mouth of the shot hole. In Figure 4 is shown a spread of six seismometers off-set from the shot hole by distances 1, 5, 10, 15, 25, and 50 feet. The slant distances increase progressively from y_1 to y_6, and the measured up-hole times should also increase progressively with off-set distance. Curves for up-hole time against

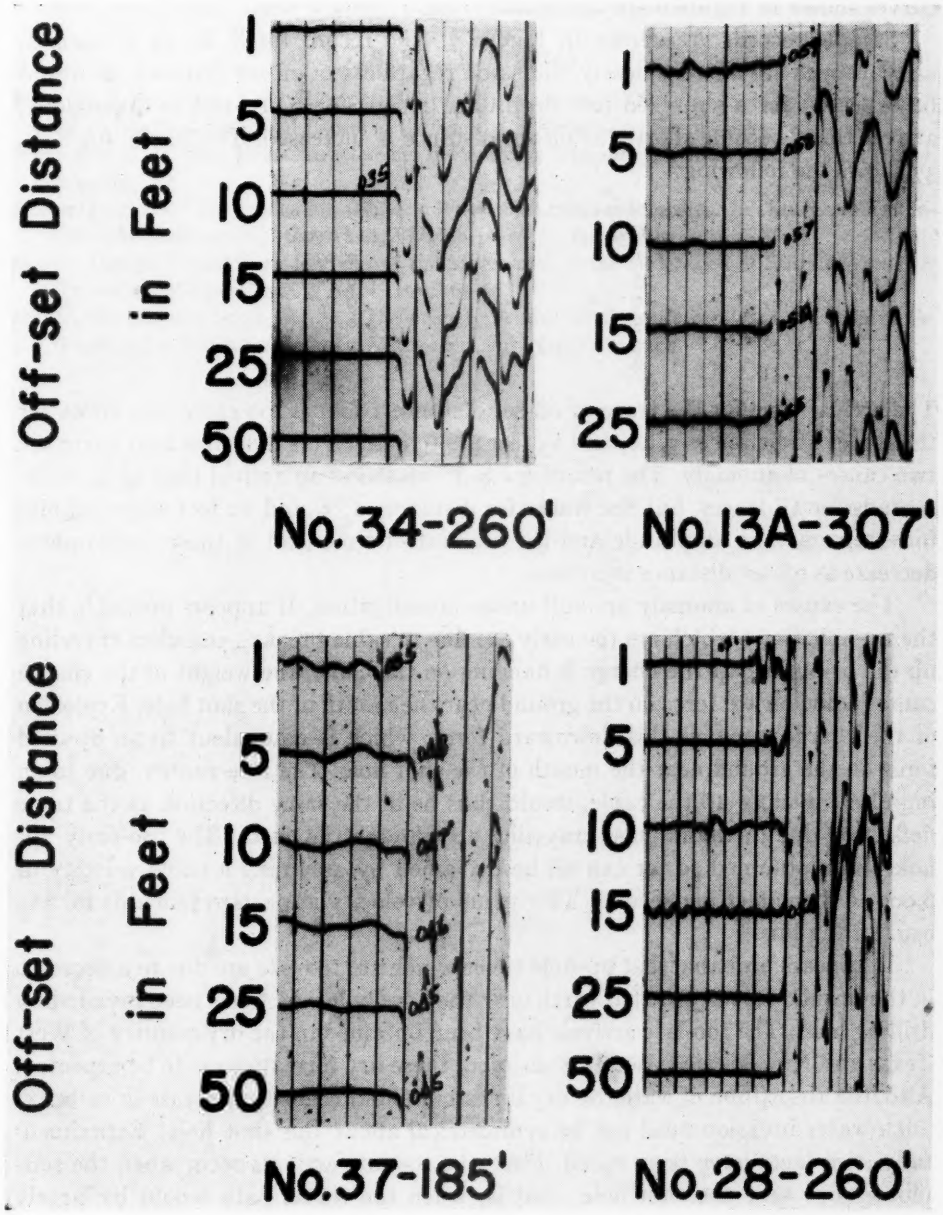

FIG. 7. Sample records.

off-set distance are shown in Figure 5 for a normal shot hole. The time-distance curves shown in Figure 6 are abnormal.

Sample records are shown in Figure 7. The record for S. P. 34 is normal; arrival times are all very nearly the same regardless of off-set distance, as would be expected for a shot 260 feet deep. The record for S. P. 13A is anomalous; arrival times become shorter as off-set distance is increased. The record for S. P. 37 shows the following:

Offset Distance in Feet	*Arrival time in Seconds*
1	0.035
5	0.048
10	0.047
15	0.046
25	0.045
50	0.045

The arrival time for the trace at off-set distance 1 foot is too early; the times for the traces at distances 5, 10, and 15 feet are too late. This indicates that there are two causes of anomaly. The record for S. P. 28 shows an arrival time of 54 milliseconds for all traces, but the traces for distances 1, 5, and 10 feet show definite fore-runners. The amplitude and the amount of time lead of these fore-runners decrease as off-set distance increases.

The causes of anomaly are still under investigation. If appears probable that the up-hole times which are too early are due to cable breaks—impulses traveling up the firing line. If the charge is hanging on the cable, the weight of the charge causes a downward force on the ground near the mouth of the shot hole. Explosion of the charge removes this downward force, which is equivalent to an upward force on the ground near the mouth of the shot hole. The fore-runner, due to an impulse traveling up the cable, would thus be in the same direction as the trace deflection due to the impulse traveling up through the earth. The too-early up-hole times obtained so far can all be explained by assuming a cable velocity of 6,000 to 8,000 feet per second. This value of velocity appears reasonable for the usual firing line.

It appears probable that up-hole times which are too late are due to a decrease in the seismic velocity of that earth near the bore hole which has been invaded by drilling mud. The too-late arrivals have been obtained in the dry country of West Texas and New Mexico. Water invasion of these dry formations is to be expected. Also, the absorption of water by dry limestone should cause a decrease in velocity. Such water invasion need not be symmetrical about the shot hole. Experimentally, two facts have been noted. First, the too-late arrivals occur when the seismometer is near the shot hole; that is, when the travel path would be largely within the invaded zone. Second, for a given off-set distance and a given charge depth, the amount of the too-late anomaly varies with azimuth; this fact fits the idea that water invasion is not symmetrical about the bore hole.

This investigation of up-hole times is still in progress, and it seems unwise to make recommendations now. Perhaps it is safe to make one—the up-hole seis-

mometer should be off-set from the shot hole by at least 20 feet in order to avoid anomalous up-hole times of the types shown in Figures 6 and 7.

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SAFETY AND GEOPHYSICAL EXPLORATION*

BART W. SORGE†

ABSTRACT

The safety and accident prevention record of geophysical operations has substantially improved during the last decade. A well-planned safety and accident prevention program which has the full support of all parts of an organization will produce results. Many advantages can be gained by improving the cooperation in safety matters among operators of geophysical crews.

American industry has made great strides during the last ten to fifteen years in providing safer working conditions. It has also made great advances in making available educational material to interest its workers in the problem of safety and accident prevention and to maintain that interest. Similarly, in our own industry we have come a long way from our early "doodlebug" days to the present. Many of the practices condoned then are now considered unsafe and are no longer permitted. The making up of charges ahead of time, the use of extremely short cap leads, the splicing of these cap leads to firing lines unshorted on the other end in the presence of dynamite, and the use of wooden dynamite magazines on shooting trucks are just a few of the unsafe practices that were then prevalent. Equipment used was also not carefully designed from a safety point of view. It was difficult to maintain, often requiring long hours of extra effort to have it ready again for the next day's work. All this produced a condition which made for a relatively high rate of accidents, resulting in a reputation that geophysical operations were necessarily dangerous and that nothing much could be done about it.

INSURANCE RATES

Comparing the past record with the present, great strides have been made. Figure 1 shows the "manual" compensation insurance rates that have been in effect in the states of Texas, Oklahoma, and California during the last twelve or thirteen years. It can be noticed that whereas the rates were approximately $6.00 per $100.00 of wages in 1938, they have decreased to a rate of approximately $2.00 per $100.00 in 1950. This is a 300 percent improvement and represents a saving of approximately $250,000.00 for each $1.00 reduction in rate in the United States alone. These "manual" compensation insurance rates for each industry are set by the respective industrial accident commissions on an annual basis and are based on actual accident experience during the preceding year. As such, they represent a fair yardstick of the performance, safetywise, of an industry.

* Presented at the St. Louis Meeting of the Society, April 23, 1951. Manuscript received by the Editor September 10, 1951.

† United Geophysical Company, Pasadena, California. Chairman, Safety Committee of *S.E.G.*, 1951–1952.

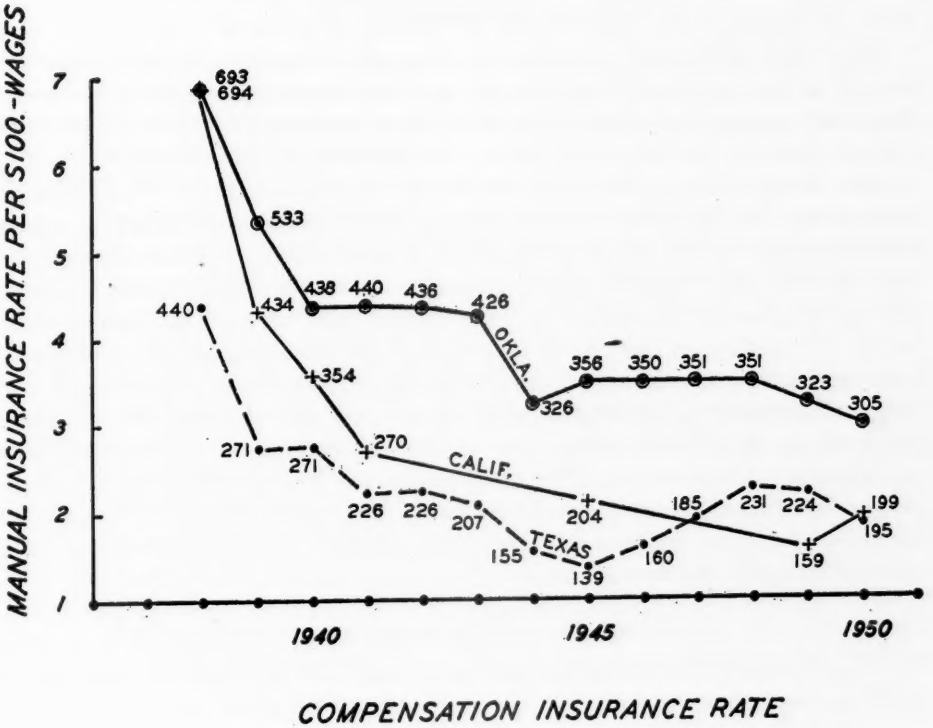
MANUAL INSURANCE RATE PER $100.-WAGES
7
6
5
4
3
2
1
693
694
533
438 440 436 426
OKLA.
326
356 350 351 351 323 305
440
434
354
271
271
270
CALIF.
204
185 231 224 199
195
226 226 207
TEXAS
155
139
160
159
1940
1945
1950
COMPENSATION INSURANCE RATE

FIG. 1

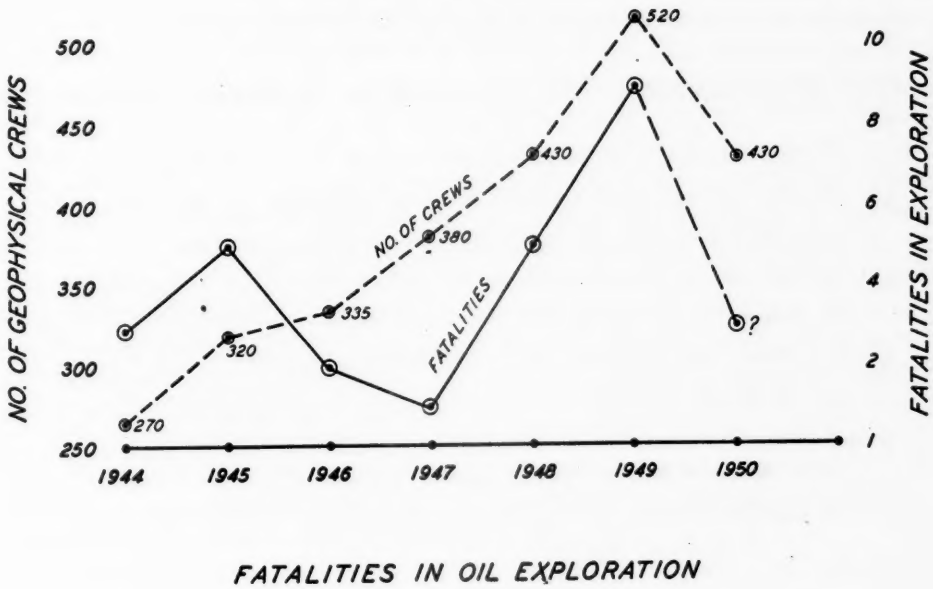
NO. OF GEOPHYSICAL CREWS
500
450
400
350
300
250
520
430
430
NO. OF CREWS
380
335
320
270
FATALITIES
?
10
8
6
4
2
1
FATALITIES IN EXPLORATION
1944
1945
1946
1947
1948
1949
1950
FATALITIES IN OIL EXPLORATION

FIG. 2

STATISTICS

The solid line on Figure 2 represents the number of fatalities in oil exploration for each of the years from 1944 through 1950. The information shown is not complete but represents a summary of information published by the American Petroleum Institute, the Bureau of Mines, and the National Safety Council.

The dashed line on this same figure represents the number of geophysical crews in the United States at the beginning of each of the years shown, as taken from the report of the *S.E.G.* Committee on Geophysical Activities. Except for the year 1947, there appears to be a correlation between a high number of fatalities and a higher rate of expansion of the number of crews working in the United States. A reduction in the rate of expansion, with the one exception, appears to bring with it a lower number of fatalities in our industry. This may be due to the fact that whenever an industry engages in a rapid rate of expansion the many problems facing it cause safety and accident prevention to receive secondary consideration. In spite of this, the geophysical industry has shown great strides in providing safer working conditions for its employees. Much, however, still needs to be done to improve the safety performance to compare favorably with other branches of the oil industry.

BASIC REQUIREMENTS FOR SAFETY PROGRAM

Figure 3 shows the ten basic requirements which are necessary for a successful accident prevention program:

1. Full and unqualified support on the part of management is an absolute must to have any safety and accident prevention program succeed. Throughout the organization, from management to supervisor to party chief, determination

BASIC REQUIREMENTS FOR SUCCESSFUL ACCIDENT PREVENTION

1. FULL SUPPORT OF MANAGEMENT
2. WELL DEFINED RESPONSIBILITIES FOR ALL PARTS OF AN ORGANIZATION
3. COMPLETE SYSTEM OF ACCIDENT REPORTS AND ANALYSES
4. ADEQUATE FIRST AID AND MEDICAL FACILITIES
5. PUBLICITY TO CREATE AND MAINTAIN INTEREST IN SAFETY
6. PROPER JOB TRAINING WITH EMPHASIS ON SAFETY
7. PROPER PROTECTIVE CLOTHING
8. USE OF ALL POSSIBLE SAFEGUARDS AND SAFETY MEASURES
9. A PROGRAM OF GOOD HOUSEKEEPING ENFORCEMENT
10. COOPERATE WITH OUTSIDE AGENCIES WHO CAN ASSIST IN SAFETY PROGRAM

FIG. 3

must exist to make the safety program a success. Without this backing it becomes extremely difficult to interest the party personnel and maintain their interest in an active safety program. Experience has shown that an exploration party's performance, safety wise, is in direct relationship to the interest that the party chief and supervisor show in the program.

2. Well defined responsibilities for all parts of an organization are necessary in any efficiently operated business organization. However, this requirement is even more essential to assure the success of an effective safety program. The responsibility for carrying out the safety program must definitely rest with the line organization, which in the case of a geophysical operator is represented by the field parties, party chiefs, supervisors, and the manager of operations. The relationship between the operating organization and the safety engineer should also be clearly understood by all. It is considered best to have the safety engineer attached to one of the staff functions, such as engineering or research, etc., instead of the operating organization. This is to prevent the interests of the safety program from being submerged to the many details and problems faced by the operating organization.

3. A complete system of accident reports and analyses is very important. It is needed to provide a proper yardstick by which to measure the success or failure of the accident prevention program. It also provides a useful guide in planning the successful elimination of the many work hazards which are the direct cause of over 90 percent of the accidents. Analysis over a period of time will show that accidents fall into very definite groupings. With this information available many of the causes can be eliminated.

4. Adequate first aid and medical facilities must be available to field crews. First aid kits, amply supplied, should be installed on all automotive equipment. It is also desirable to have two or more of a crew's personnel trained in first aid. This can often be accomplished by making arrangements with the Red Cross in the area where a crew is working. A series of first aid instructions during evening hours, attended by a representative number of the crew's personnel, can often be arranged. It is also important that the majority of men on a crew know the names and addresses of doctors available to them should a serious accident occur.

5. Continuous publicity is necessary to create and maintain an interest in the safety program. Included in this is the sending of appropriate safety posters, bulletins, and other materials to the parties so that the party safety committees and the party chiefs can intelligently plan their accident prevention activities. It is necessary to continuously remind the workers on a geophysical crew that safety and accident prevention is necessary and designed for their own benefit.

6. Proper job training, with particular emphasis on safety, is a necessity. This training is very important for new employees and for all employees at times when new equipment or new procedures are introduced.

7. Proper protective clothing should be worn by all. It should be an absolute must that shooters, drillers, and their helpers wear safety hats, and that leather

gloves be worn to prevent numerous hand injuries. Safety gloves for the personnel winding in geophone cables are also essential, and safety goggles and safety shoes should be used whenever they are necessary.

8. All possible safeguards and safety measures should be employed to protect the general public as well as the workers from possible dangers in connection with geophysical exploration work. State and Federal laws closely govern the handling, transportation, and storing of dynamite and caps; these should be strictly observed. All State rules and regulations in connection with the use of public highways must be observed to avoid unsafe conditions. When working along highways

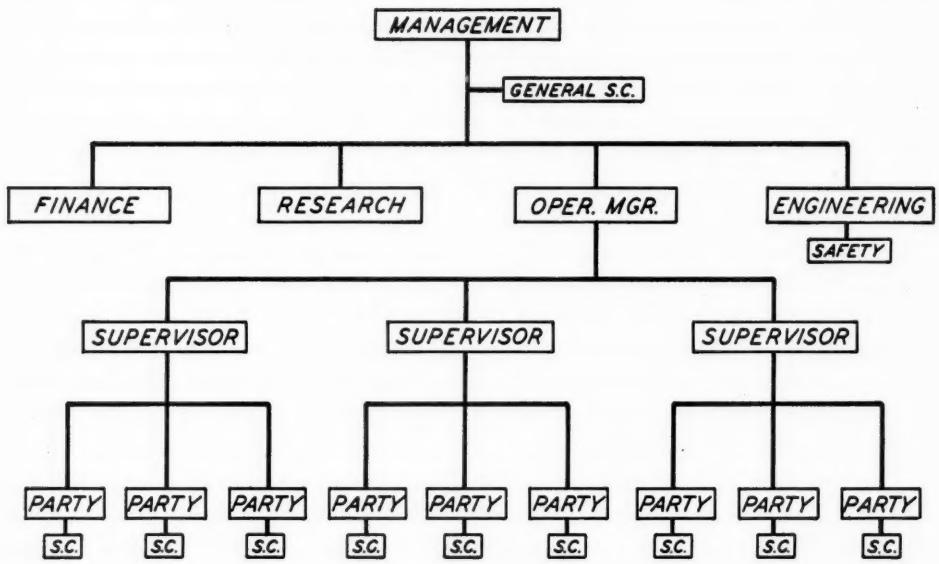

FIG. 4

signs should be placed in both directions warning traffic that work is being conducted. All vehicles should be equipped with flares, chains, and other equipment to minimize accident producing conditions as much as possible. Safe-driving speeds governed by road conditions rather than miles per hour speed limits should be observed at all times.

9. A program of continuous good housekeeping enforcement is very essential to minimize accident producing conditions. This requires that equipment on all trucks be stored and carried in an orderly manner and that drillers place tools and materials in an orderly manner around the shot-hole location while drilling.

10. Cooperation with all possible outside agencies, such as the National Safety Council, the many State industrial accident commissions, the American Petroleum Institute, and the United States Bureau of Mines, is essential. These organizations are presently doing a great amount of work from which the geophysical industry could benefit much more if it would cooperate with the organizations more fully than is now the case. These agencies are doing considerable

work to gather and publish accident statistics each year to serve as a guide to the industry. Unfortunately, however, these agencies are receiving cooperation from only a small part of the operators of our industry.

ORGANIZATION OF A PROGRAM

Figure 4 shows the organizational arrangement for an effective safety program. A top-level general safety committee, usually consisting of the manager of operations, the personnel manager, the insurance specialist, and a safety engineer, sets the policy for the safety program. Wherever possible the president or head of the organization should also be a member of this policy-making committee. It is very important that the manager of operations or chief supervisor, whose responsibility it is to direct the operation of all the company's crews, be on this committee. Responsibility for carrying out a safety program and providing safe accident-free working conditions rests definitely with that department. The safety engineer, usually attached to one of the staff functions, merely acts in an advisory and planning capacity. Unless this is thoroughly understood by all, it can be very difficult to start, as well as continue, an effective accident prevention program. It is the duty of the safety engineer to sell and keep sold the value of safety to all parties, party chiefs, and supervisors on one hand, and management of the company on the other.

Each party has its own safety committee. It usually consists of three or five men with a chairman. The members of this committee should represent the various functions of geophysical exploration work. It has been found useful to have at least one surveyor or office man on the committee to be its secretary. The real success or failure of an accident prevention program depends largely on this committee. From experience we have found that the success of a party, safety-wise, is in direct relationship to the interest and effort that the members of the party safety committee put forth.

ACCIDENT EXPERIENCE

Figure 5 shows accident experience information for several representative companies. The lower portion shows the accident frequency rate; that is, the number of lost-time injuries per million man hours worked. On the upper part is shown the severity rate, which represents the number of man days lost per one thousand hours worked. The dashed and dotted lines on these two graphs represent the experience of a company which instituted an active safety program in 1947. Examination of these curves shows that from that time to the present both accident frequency and severity reduced appreciably and have stayed low since. The solid line curves represent the experience of another company which initiated an active safety program in 1950. In this case, too, an immediate sharp drop in the accident experience of this company resulted. There are many other companies that have achieved similar results after instituting an active and effective safety and accident prevention program. It is interesting to note that almost none of the crews of geophysical operators who have had an active safety program for ten years or longer have contributed to the deaths shown on Figure 2.

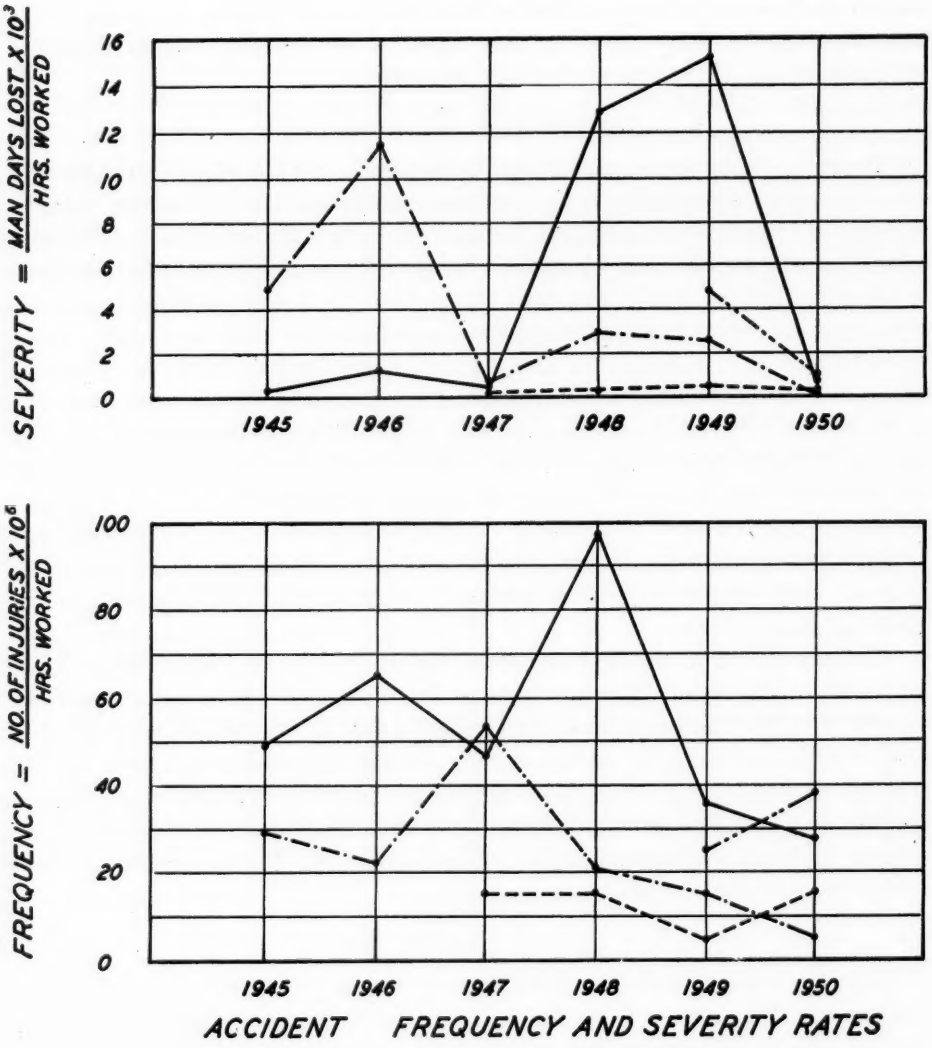

FIG. 5

The greatest barrier towards further reduction in accidents in the geophysical industry is the hesitancy on the part of individual organizations to cooperate with outside agencies interested in safety or with each other. This shortcoming is fortunately being eliminated at the present time. A few months ago several geophysical operators, including oil companies and contracting organizations, instituted a geophysical accident information exchange. In the short time since the inception of this arrangement participants have doubled in number. Information is exchanged monthly on the number and causes of accidents that have occurred during the preceding month. In some cases safety manuals and other safety information has also been exchanged on an individual basis. Even in this rela-

tively short time the cooperative effort has proven to be very beneficial. It was reasoned, when starting this cooperative effort, that even though the participants are competitors, business-wise, safety should be a non-competitive item. A free exchange of information on accidents and their causes permits the cooperating companies to remove or correct similar accident-producing conditions in their operations. Much of the information exchanged is used by participating organizations to intelligently plan their safety and accident prevention program. It is also used by the participants' party safety committees in their endeavor to reduce or eliminate accident-producing conditions on the exploration parties.

An industry-wide safety effort offers many advantages. It makes it possible for all workers engaged in the industry to be better trained and more efficient. This is an important item when workers change employment within the industry. Cooperation will also have a tendency to lower compensation insurance rates in states and countries where these rates are established or regulated by the losses suffered by an industry as a whole. Good accident experience on the part of all geophysical exploration units operating in a state or country will automatically lower the "manual" compensation insurance rates for all. This can be noticed on Figure 1, which shows the "manual" insurance rates for geophysical operations of several states.

Cooperation among companies will also permit standardization of educational material, stressing safety, such as bulletins and posters by the *National Safety Council*, the *United States Bureau of Mines*, and the *American Petroleum Institute*. The industry's cooperative efforts will encourage these agencies to publish these posters and issue accident prevention materials which are geared to the specific problems and needs of our industry. All three of the above named organizations are presently engaged in compiling and publishing accident statistical information. They all agree that they could do a much better and more complete job and have available more conclusive information if they received the cooperation of all geophysical operators instead of only a few.

SPECIAL SAFETY COMMITTEE OF S.E.G.

To further the cause of safety and accident prevention, the Society of Exploration Geophysicists has established a special committee on safety. It will be this committee's duty to cooperate with the agencies interested in safety and to secure the wholehearted cooperation of our industry with them. It will also be part of this committee's activity to create an interest in safety and accident prevention among the operators of geophysical crews and to distribute and make available to the industry safety posters and other literature to further the cause of safe geophysical operations.

Much has been accomplished along these lines during the last few years, but much more still needs to be done to improve our industry's safety record. This can and will be accomplished by the wholehearted cooperation of geophysical operators with each other, with the established safety agencies, and with the special committee on safety of the S.E.G.

STUDIES IN NON-STRUCTURAL PETROLEUM PROSPECTING

II. THE COMPARATIVE RESOLUTION OF PERTINENT GULF COAST REFRACTION ANOMALIES*

E. E. ROSAIRE†

ABSTRACT

For the case of low-relief structure associated with petroleum accumulation, the non-structural working hypothesis postulates the observation of refraction fan anomalies with characteristics which are unique when compared with those of the refraction fan anomalies postulated by the geophysical structural working hypothesis generally accepted for the resolution of refraction fan anomalies.

These unique characteristics are observable magnitude on depths of survey too shallow to intercept the underlying structure, double-peaked maximum configuration, off-structural orientation of maximum leads, and change in type of configuration as the survey depth increases to structural interception.

Case treatments are shown where such structurally forbidden refraction fan anomalies were observed across low-relief structure associated with petroleum accumulation, subsurface conditions which were revealed by subsequent development. These case treatments are substantiating evidence for the non-structural working hypothesis in Gulf Coast refraction prospecting.

INTRODUCTION

Form of Critical Test

In the preceding study,[1] a critical test was described for the proposed non-structural working hypothesis, based upon the identification of the unique characteristics postulated for the structurally forbidden near-surface, significant stratigraphic anomaly. These unique characteristics were (1) an observable magnitude at depths of survey too shallow to intercept an underlying lithologic structure, (2), a configuration conformable with the outline of a significant area rather than with the area itself, (3), a maximum expression of that anomaly oriented with respect to the edge of a significant area rather than to the area itself, and, (4) a change in type of that configuration, rather than in the absolute magnitude of the anomaly, as the survey depth increases.

In his personal files from the Gulf Coast refraction campaign of 1924–1931, the writer found several instances of refraction fans across low-relief structure associated with petroleum accumulation, subsurface conditions which had been revealed by subsequent development. Material was at hand, then, for investigating the critical corollaries of the proposed non-structural working hypothesis with respect to the near-surface significant stratigraphic anomaly, the

* Much of the material in this study was presented before the Society at the Eleventh Annual Meeting, Houston, Texas, April 1–4, 1941, as part of the paper entitled "An Analysis of the Refraction Collapse of 1930" (Printed Program, pp. 5–6). Manuscript received by the Editor June 14, 1950.

† Subterrex, Houston, Texas.

[1] E. E. Rosaire, "I. A Non-Structural Working Hypothesis for Petroleum Prospecting," *Geophysics, Vol. XVI*, No. 3 (1951), 456–461.

existence of which is forbidden by the then and currently accepted geophysical structural working hypothesis.*

However, since many of those now active in seismic prospecting embarked upon that career after the Gulf Coast refraction campaign terminated, some background discussion may be appropriate, and will be included where pertinent.

Structural Relief

Structural relief not only is a relative differentiation, but also is made on the basis of an elastic yardstick. A low-relief structure at one depth, or on yesterday's survey, may be a high-relief structure at a greater depth, or on today's survey. The proper referent is the depth of the survey at which the relief is measured.

This study is based upon refraction surveys completed twenty and more years ago. The terms "high-," "intermediate-" and "low-relief" structure thus refer to structural relief in terms of the refraction prospecting of that period, with referent depths of survey much shallower than those which characterize the current reflection prospecting to much greater depths.

The Near-Surface Significant Stratigraphic Anomaly in Refraction Prospecting

The objective of this study is a test of the non-structural hypothesis in refraction prospecting based on the identification of near-surface significant stratigraphic anomalies on the basis of their postulated unique characteristics.

The special stratigraphic sub-hypothesis can be restated as follows so far as it pertains to the near-surface significant stratigraphic anomaly in refraction prospecting.†

A localized increase in seismic velocity tends to take place in those sediments immediately adjacent to the outline of the near-surface projection of petroleum accumulation. When fully and uniformly developed, such a near-surface significant stratigraphic anomaly takes the form of a halo or aureole outlining the near-surface projection of petroleum accumulation.

The magnitude of such an anomaly appears to bear no definite relationship to the depth of petroleum accumulation or to the depth or relief of associated structure. Such a near-surface significant stratigraphic anomaly need not be accompanied by nor associated with structural deformation, but appears to originate wholly in stratigraphic variations in primary lithology associated with the presence of petroleum accumulation.

Under favorable conditions, the magnitude of a near-surface significant stratigraphic anomaly, relative to its background, may be great enough to be observed in

* Hereafter in these studies, for the sake of brevity, "structural hypothesis" and "non-structural hypothesis" will be used instead of the more specific "geophysical structural working hypothesis" and "non-structural working hypothesis" used and generally defined in the previous study.

† Reference to a "near-surface" significant stratigraphic anomaly should be understood as stressing its *existence* at near-surface depths, not as necessarily restricting it thereto. Thus, in Figure 2, following, the "near-surface" significant stratigraphic anomalies are shown as persisting with depth down to the petroleum accumulation.

refraction prospecting. Particularly favorable conditions are a regional background of normally low seismic velocities and negligible (lithologic) structural relief at the effective depth of penetration of the seismic survey.

Seismic Velocity Structure

The reflection seismologist is concerned primarily with the passage of seismic waves through elastic media and *to* seismically identifiable horizons; the refraction seismologist was concerned primarily with the passage of seismic waves through elastic media and *along* seismically identifiable horizons. In general, the latter was concerned with stratification in terms of seismic velocities and, in particular, with sedimentary provinces where that stratification involved an increase in seismic velocity with depth.

Refraction prospecting proceeded by determining the depth to markers identified by particular seismic velocities, i.e., mapping the structure of seismic velocity horizons. In the Permian Basin, mapping proceeded by such depth determinations from profiles on a predetermined grid; the regional and local seismic velocity structure were established by contouring those depths. In the Gulf Coast, if the arrival-times around a fan were "normal" within observational error, the conclusion was that the "normal" increase of seismic velocity with depth prevailed. An observed local travel-time shortening was attributed to a locally abnormal increase of seismic velocity with depth, i.e., to the existence of local uplift or structure in the seismic velocity horizons.

In refraction prospecting the significant anomaly was one characterized by arrival times shorter than normal, usually referred to as "leads," "accelerations" or "fast shots." In those lithologic provinces characterized by seismic velocities which increased with depth, such an anomaly, then, would be due to local uplift in one, or more than one, seismic velocity horizon, or, in more familiar parlance, a seismic velocity "high."

VERTICAL CROSS SECTIONS, SEISMIC VELOCITY STRUCTURES, FIGURES 1 AND 2

Structural Hypothesis (Fig. 1)

In the resolution of refraction fan anomalies by the structural hypothesis, the basic assumptions were that a significant seismic velocity structure could originate from, and only from, lithologic structure, and, within the limits of observational error, the seismic velocity horizons were conformable with and so did not transgress the primary lithologic horizons (i.e., seismic velocity structure necessarily should be conformable with lithologic structure). In such resolution, no consideration was given to the possibility that the observed seismic velocity structure might originate, partly or wholly, in stratigraphic variation in primary lithology associated with the presence of petroleum accumulation; the tacit assumption was that no such effects were to be expected.

Thus, Figure 1 shows the conformable relationship between the seismic veloc-

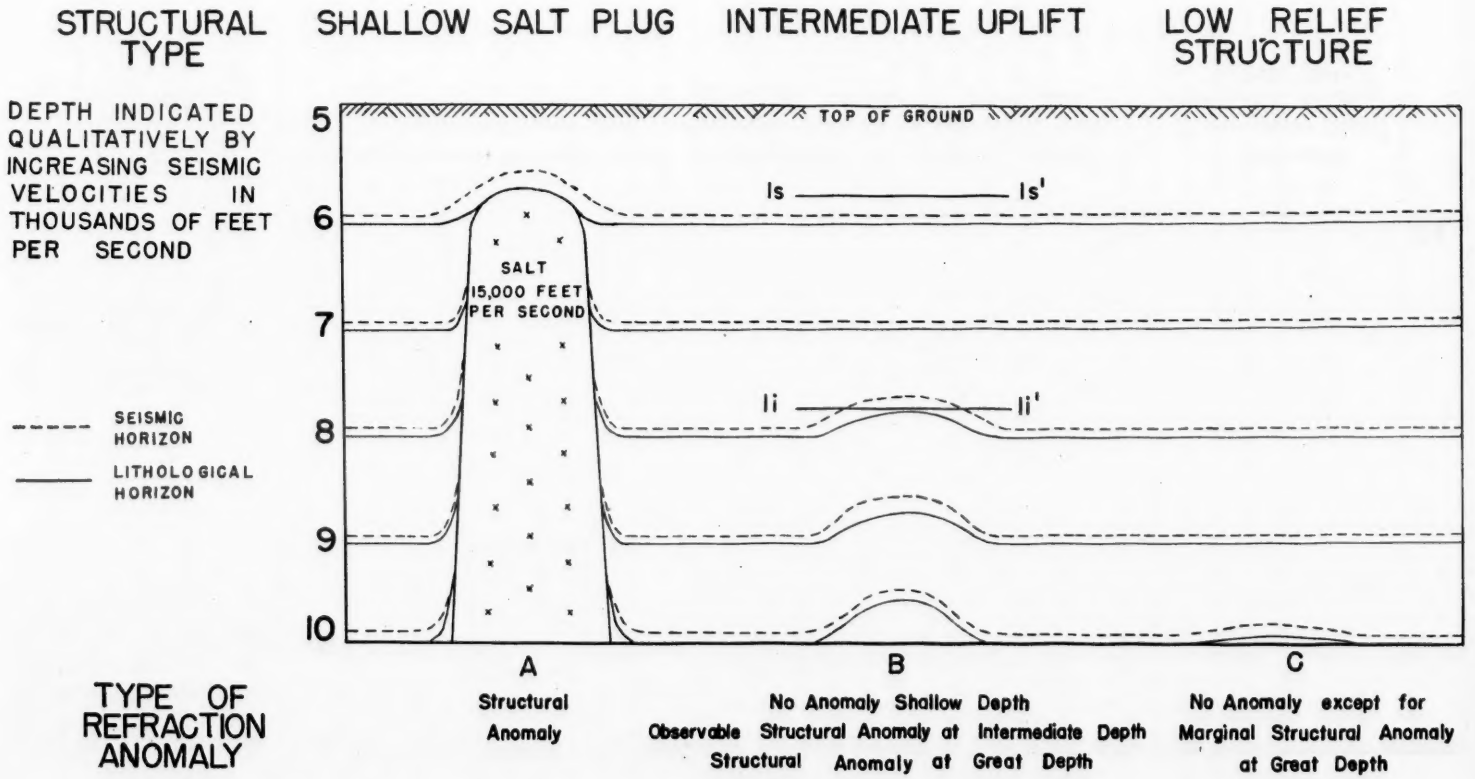

FIG. 1. Diagrammetric vertical seismic velocity cross section for the structural hypothesis and the special structural sub-hypothesis.

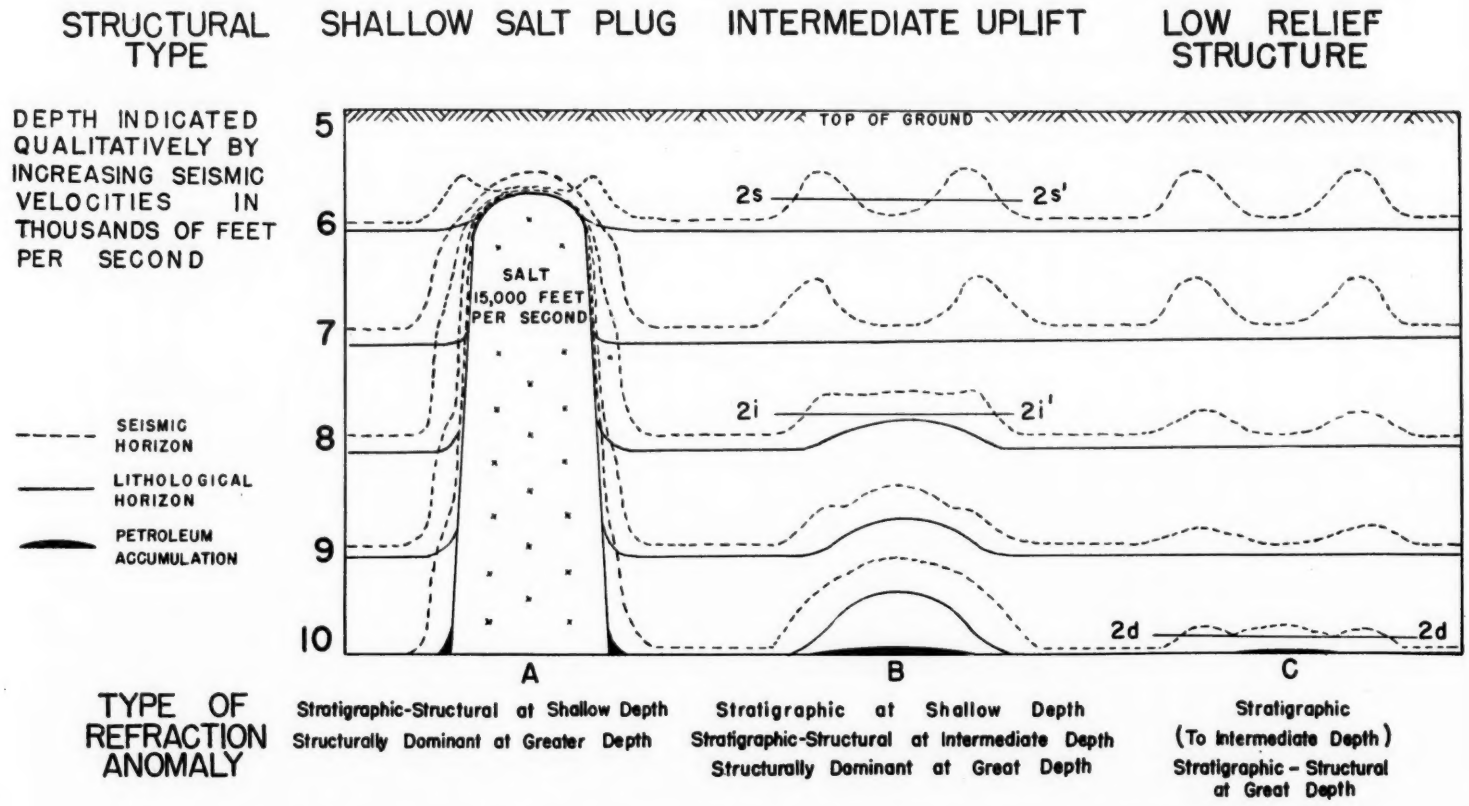

FIG. 2. Diagrammetric vertical seismic velocity cross section for the general case, non-structural hypothesis.

ity horizons and the lithologic horizons assumed in resolution by the structural hypothesis.

Non-Structural Hypothesis (*Figs. 1 and 2*)

In resolution by the non-structural hypothesis, the basic assumption is that a seismic velocity structure may originate not only in lithologic structure, but also in the stratigraphic changes in (primary) lithology associated with the presence of petroleum accumulation. Thus, the presumption is that the seismic velocity horizons may or may not be conformable with, and may or may not transgress, the primary lithologic horizons (i.e., seismic velocity structure need not necessarily be conformable with lithologic structure).

Consequently, resolution by the non-structural hypothesis anticipates a gradation in types of significant refraction anomalies. At one extreme is the significant structural anomaly, a seismic velocity structure which originates wholly in, and *is* conformable with, lithologic structure. At the other extreme is the significant stratigraphic anomaly, which originates wholly in the stratigraphic changes in (primary) lithology associated with the presence of petroleum accumulation and *is not* conformable with the (primary) lithologic structure. In between are those significant "mixed" anomalies which originate partly in lithologic structure and partly in the stratigraphic changes in (primary) lithology associated with the presence of petroleum accumulation. Points on that gradation could be classified as "structurally dominant," "structural-stratigraphic," "stratigraphic-structural," and "stratigraphically dominant." The writer groups all such "mixed" anomalies as "stratigraphic-structural."

The non-structural hypothesis thus involves two sub-hypotheses, the special structural and the special stratigraphic hypotheses. Resolution by the non-structural hypothesis thus depends upon an identification of an observed anomaly as "structural," "stratigraphic," or "stratigraphic-structural" ("mixed"), and the utilization of one, or both, of these sub-hypotheses, depending upon whether the anomaly is classified as "pure" or "mixed." These sub-hypotheses were stated, in general terms, in the preceding study.

In the absence of observable anomalies originating in significant stratigraphic variations in lithology, the non-structural hypothesis reverts to the special structural hypothesis which, as pointed out in the foregoing study, is the practical equivalent of the geophysical structural working hypothesis. Thus, Figure 1 also illustrates one extreme of the gradation in types of anomalies anticipated by the non-structural working hypothesis, the special case in which the seismic velocity horizons *are* conformable with the lithologic horizons.

Figure 2 illustrates* other points on, including the other extreme of, that

* Obviously, it would be unrealistic to conclude that those portions of the seismic velocity structure which, in Figure 2, deviate from the there pictured "lithologic" structure do so independently of the lithology; presumably the seismic velocity horizons *are* conformable with some one, or more than one, lithologic property. The "lithologic" horizons drawn in Figure 2 are considered to be the same "primary lithologic" horizons shown in Figure 1, i.e., the "lithologic" horizons shown in Figure 2 are

gradation in seismic velocity structure anticipated by the nonstructural hypothesis. Thus, as we consider decreasing depths of survey, in Figure 2A the seismic velocity structure (in terms of the originating lithologic anomaly) changes from structurally dominant at great depth to structural-stratigraphic at shallow depth. In Figure 2B, the seismic velocity structure (in terms of the originating lithologic anomaly) changes from structural-stratigraphic at great depth, the stratigraphic-structural at intermediate depth, and, finally, to stratigraphic at shallow depth. In Figure 2C, the seismic velocity structure (in terms of the originating lithologic anomaly) changes from stratigraphically dominant at great depth to stratigraphic at shallow depth.

HORIZONTAL CROSS SECTIONS, FIGURE 3

Assume that the lithologic structures shown in Figures 1 and 2 are circular in cross section. Then consider the horizontal cross sections of the seismic velocity structures at the levels 1s-1s′ and 1i-1i′ in Figure 1B, 2s-2s′ and 2i-2i′ in Figure 2B, and 2d-2d′ in Figure 2C. ("s," "i," and "d" are abbreviations for "shallow," "intermediate" and "deep," respectively.)

Then, at the level 1s-1s′, no local seismic velocity structure exists. At the level 1i-1i′, a seismic velocity structure exists, due, in terms of the originating lithologic anomaly, wholly to lithologic structure; the intercepted area of that (significant structural) seismic velocity structure is circular, with a radius, r, as shown in Figure 3Aa.

At the level 2s-2s′, a local seismic velocity structure exists, due, in terms of the originating lithologic anomaly, wholly to significant stratigraphic variations in lithology; the intercepted area of that (significant stratigraphic) seismic velocity structure is a halo, with a width Δr, as shown in Figure 3Ba. At the level 2i-2i′, a local seismic velocity structure exists, due, in terms of the originating lithologic anomaly, to both lithologic structure and significant stratigraphic variations in lithology; the intercepted area of that (significant stratigraphic-structural) seismic velocity structure is circular, with a radius $(r+\Delta r)$, as shown in Figure 3Cb.

At the level 2d-2d′, a seismic velocity structure exists, due, in terms of the originating lithologic anomalies, almost entirely to a combination of the near-surface and near-deposit significant variations in lithology; the intercepted area of that (significant combination stratigraphic) seismic velocity structure is circular, with a radius $(r+\Delta r)$, as shown in Figure 3Cb. Such an almost pure (some structural effect is suggested there in Figure 2C) combination significant stratigraphic anomaly thus should have characteristics similar to the stratigraphic-structural and

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supposed to be shown as they would have been had no significant variations taken place in that "primary lithology" as a result of petroleum accumulation. There exists an admitted inadequacy in this verbal description.

The regretted but probably ensuing confusion may or may not be compounded by the introduction of another attempt at verbal description, the "originating lithologic anomaly," which may be structural, stratigraphic-structural, or stratigraphic.

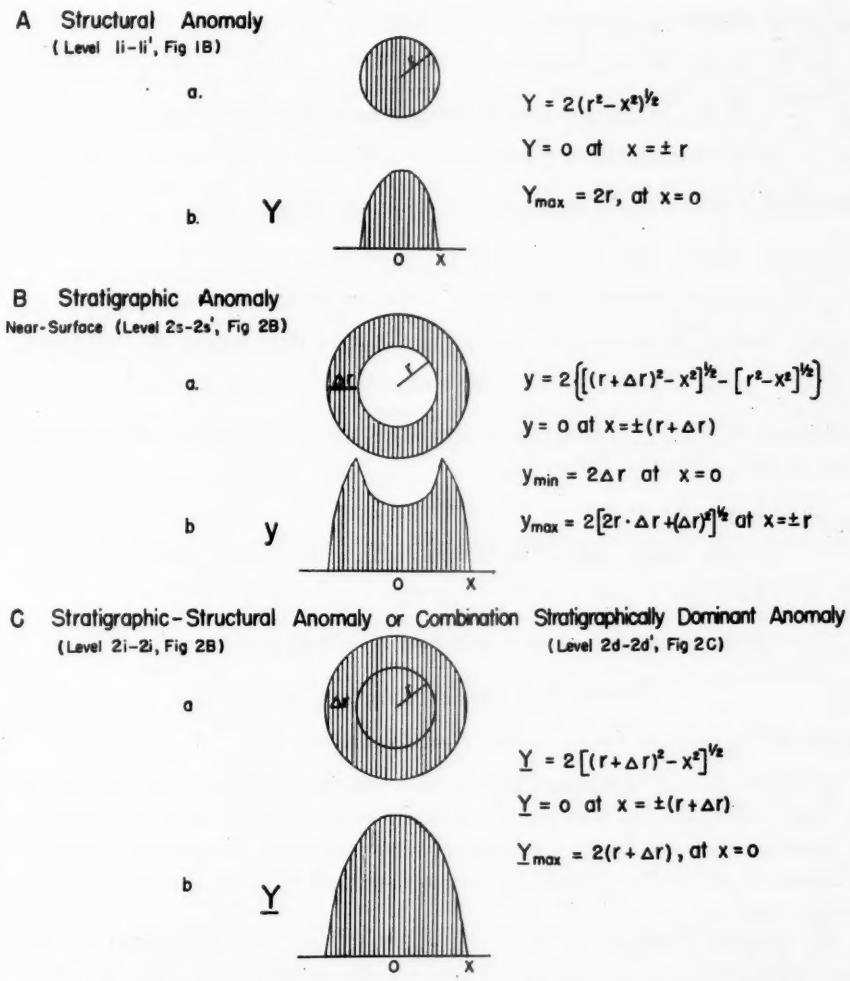


FIG. 3. Distance relationships. A. Structural anomaly. B. Near-surface significant stratigraphic anomaly. C. Stratigraphic-structural or combination stratigraphically dominant anomaly.

the structural types of significant refraction anomalies anticipated by the non-structural hypothesis.

Distance Relationships for Horizontal Cross Sections (Fig. 3)

If the linear distances through (and only through) these cross sections are plotted against their perpendicular distances from the central vertical axes of the structures, the following relationships hold.

Level 1s-1s' (No seismic velocity structure intercepted, and so not shown in Figure 3)

$$(y) = ox.$$

Level 1i-1i′ (Structural anomaly, Figure 3Ab)

$$Y = 2(r^2 - x^2)^{1/2}$$

Y is a single-peaked maximum, with the maximum lead,

$Y = 2r$, at $x = 0$, while $Y = 0$ at $x = \pm r$.

Level 2s-2s′ (Near-surface stratigraphic anomaly, Figure 3Bb)

$$y = 2\left\{\left[(r + \Delta r)^2 - x^2\right]^{1/2} - \left[r^2 - x^2\right]^{1/2}\right\}$$

y is a double-peaked maximum, with two maximum expressions,

$y = 2\left[2r \cdot \Delta r + (\Delta r)^2\right]^{1/2}$, at $x = \pm r$, a central minimum expression,

$y = 2\Delta r$, at $x = 0$, while $y = 0$ at $x = \pm (r + \Delta r)$.

Level 2i-2i′ or 2d-d′ (Stratigraphic-structural, or combination stratigraphically dominant, anomaly, Figure 3Cb)

$$Y = 2\left[(r + \Delta r)^2 - x^2\right]^{1/2}$$

Y is a single-peaked maximum, with a maximum lead,

$Y = 2(r + \Delta r)$,

$Y = 2(r + \Delta r)$, at $x = 0$, while $Y = 0$ at $x = \pm (r + \Delta r)$.

POSTULATED REFRACTION FAN ANOMALIES

Graphical Presentation for Refraction Fan Anomalies

In the refraction campaign, two tactics were used, the profile and the fan. In the Gulf Coast, the fan was used to a much greater extent than the profile, since the usual assignment there was general reconnaissance for structure rather than the detail of structure already known or inferred (as was the usual case in the Permian Basin).

The graphical display of the refraction fan data, first developed by the Seismos* interpreters, was to plot the magnitude of the travel time anomaly (for each recorder position) along the shot-recorder ray about an arc of convenient radius, drawn with the shot point as a center and considered as the line of zero travel time anomaly (i.e., normal arrival time). Two conventions were used.

The Seismos and some American computers followed the convention adopted in polar coordinates, in which a shortening (i.e., an anomaly with a minus sign, sometimes called an "acceleration") of the travel-time below normal was plotted towards the shot point (origin). An increase (i.e., an anomaly with a plus sign, sometimes called a "deceleration") of the travel-time above normal was plotted away from the shot point (origin).†

* The Seismos, G.M.B.H., was a German organization, headed by Dr. Ludger Mintrop, which introduced the refraction method into the Western Hemisphere circa 1923.

† Vide *Geophysical Case Histories, Vol. I*, p. 164.

The writer preferred to reverse this convention, plotting minus travel-time anomalies away from the shot point and plus-valued travel-time anomalies towards the shot point. Thereby the lines joining the (so indicated) travel-time anomalies on adjacent shot-recorder rays tended to display a configuration which approximated the outline of the seismic wave front in the general vicinity of the recorder positions.† In the illustrations of the refraction fan anomalies which follow, the writer has continued to follow this latter convention.

Lead Proportional to Distance Through Seismic Velocity Structure

The relationship between the distance through the intercept of the seismic velocity structure, as shown in Figure 3, and the corresponding travel-time "lead," is as follows, if refraction effects are neglected.

Given a distance (y) through a seismic velocity structure where the normal seismic velocity in the background is V_1, and the abnormal seismic velocity through the seismic velocity structure is V_h.

Then the lead (L) can be derived as follows.

For a distance (y) through normal lithology, the time (T_1) is

$$T_1 = y/V_1.$$

For a distance (y) through the abnormal velocity, the time (T_h) is

$$T_h = y/V_h.$$

Then

$$L = T_1 - T_h = y(V_h - V_1)/V_h \cdot V_1$$

and so

$$L \propto y.$$

Thus, the observed travel-time shortening should be proportional to the distance through the intercepted seismic velocity structure. In the graphical representation of the postulated refraction fan anomalies (Fig. 4 and 5), then, the travel-time anomaly reasonably can be taken as proportional to the distance which the seismic ray travels through the seismic velocity structure, i.e., to that portion of the seismic velocity structure intercepted by the seismic ray.

*Refraction Fan Anomalies, Structural Hypothesis (Fig. 4)**

Figures 4A and 4B show refraction fans which are presumed to intercept Figure 1B at levels 1s-1s′ and 1i-1i′, respectively.

† Vide *Geophysical Case Histories, Vol. I*, p. 166.

* In Figures 4 and 5, for convenience, the *distances* intercepted in the seismic velocity structures are shown proportional to the observed *leads*, and refraction efforts have been neglected. No attempt has been made to determine what those leads would have been on the basis of the seismic velocity relationships postulated in Figures 1 and 2.

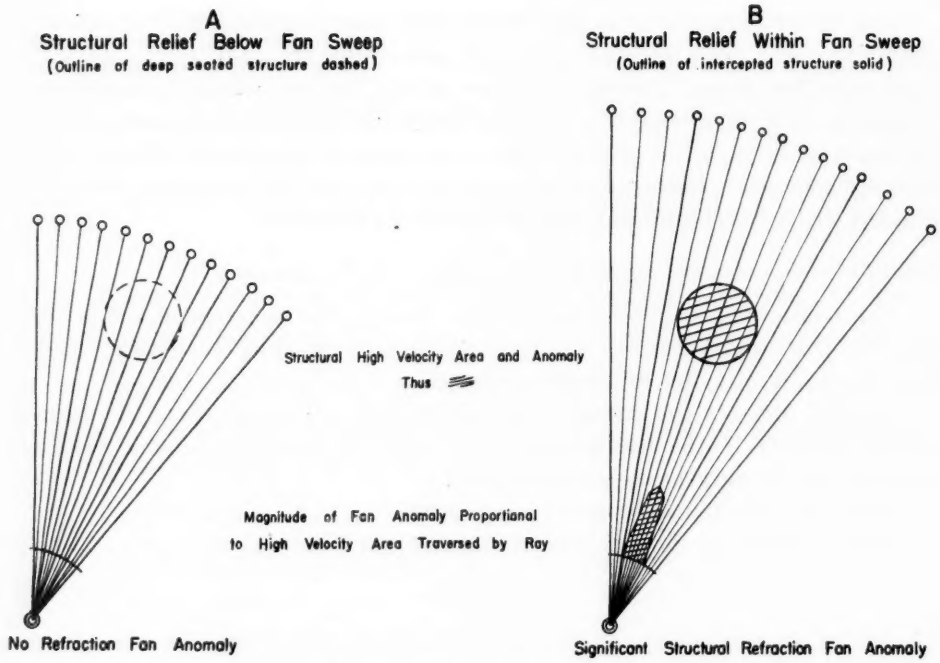

A
Structural Relief Below Fan Sweep
(Outline of deep seated structure dashed)
B
Structural Relief Within Fan Sweep
(Outline of intercepted structure solid)
Structural High Velocity Area and Anomaly
Thus
Magnitude of Fan Anomaly Proportional
to High Velocity Area Traversed by Ray
No Refraction Fan Anomaly
Significant Structural Refraction Fan Anomaly

FIG. 4. Refraction fan travel-time anomalies on the basis of the structural hypothesis and the special structural sub-hypothesis. A. Structural relief below fan sweep. B. Structural relief within fan sweep.

No anomaly is shown in Figure 4A, since there is no interception of a seismic velocity structure at level 1s-1s′ in Figure 1B.

An anomaly is shown in Figure 4B, since a seismic velocity structure is intercepted at level 1i-1i′ in Figure 1B. That observed, significant structural anomaly is similar in configuration to the distance relationship shown in Figure 3Ab (except for the distortion resulting from the use of a curved rather than a straight base line).

Thus, for the case where the seismic velocities are conformable with the primary lithology, and the seismic velocity structure originates wholly in and is conformable with lithologic structure (with characteristics as specified), the following corollaries result.

1. If the survey does not intercept an underlying lithologic structure, no anomaly (i.e., an anomaly of zero magnitude) should be observed.

2. If the survey does intercept an underlying (seismic velocity structure which is conformable with) lithologic structure, a significant structural anomaly should be observed.

A. The configuration of that observed, significant structural anomaly should be a single-peaked maximum.

B. The maximum expression (i.e., the maximum lead) of that observed anom-

aly should be properly oriented with respect to the surface projection of the intercepted area of the lithologic structure, i.e., should be observed on that seismic ray which has the maximum intercept of (the seismic velocity structure which is conformable with) the lithologic structure.

3. Thus, as the survey depth increases, a change in *absolute magnitude* may take place in the anomaly observed, i.e., from an anomaly of zero magnitude (observed on a survey too shallow to intercept an underlying lithologic structure) to an anomaly of observable magnitude (on a survey deep enough to intercept an underlying lithologic structure). In other words, the magnitude of the observed anomaly should be directly proportional to the magnitude of the intercepted area of the lithologic structure.

Refraction Fan Anomalies, Non-Structural Hypothesis (Figs. 4 and 5)

Special Case

In the absence of observable significant stratigraphic anomalies, the non-structural hypothesis reverts to the special structural sub-hypothesis which, as pointed out earlier, is the practical equivalent of the structural hypothesis.

Thus, Figure 4 also shows the refraction fan anomalies anticipated in resolution by the special structural hypothesis, i.e., those which should be observed in the absence of observable significant stratigraphic anomalies.

General Case

Figures 5A and 5B show refraction fan anomalies which are presumed to result from the interception of Figure 2B at the levels 2s-2s′ and 2i-2i′, respectively.

An anomaly is shown in Figure 5A because a seismic velocity structure is intercepted at level 2s-2s′ in Figure 2B. An anomaly is shown in Figure 5B because a seismic velocity structure is intercepted (at level 2i-2i′ in Figure 2B). The configurations of these postulated refraction fan anomalies are similar to the configurations of the distance relationships in Figures 3Bb and 3Cb, respectively (except for the distortion resulting from the use of a curved rather than a straight base line).

Thus, for the case where the seismic velocity structure originates partly in lithologic structure (with the characteristics specified) and partly in significant stratigraphic variations in primary lithology associated with conformable petroleum accumulation, the following corollaries result.

4. If the survey does not intercept an underlying *lithologic* structure, a near-surface, significant stratigraphic anomaly should be observed.

A. The configuration of that observed anomaly should be a double-peaked maximum.

B. The maximum expression of that double-peaked maximum (i.e., the maximum leads) should bracket the surface projection of the petroleum accumulation.

C. The central minimum of that double-peaked maximum should be properly oriented with respect to the surface projection of the petroleum accumulation.

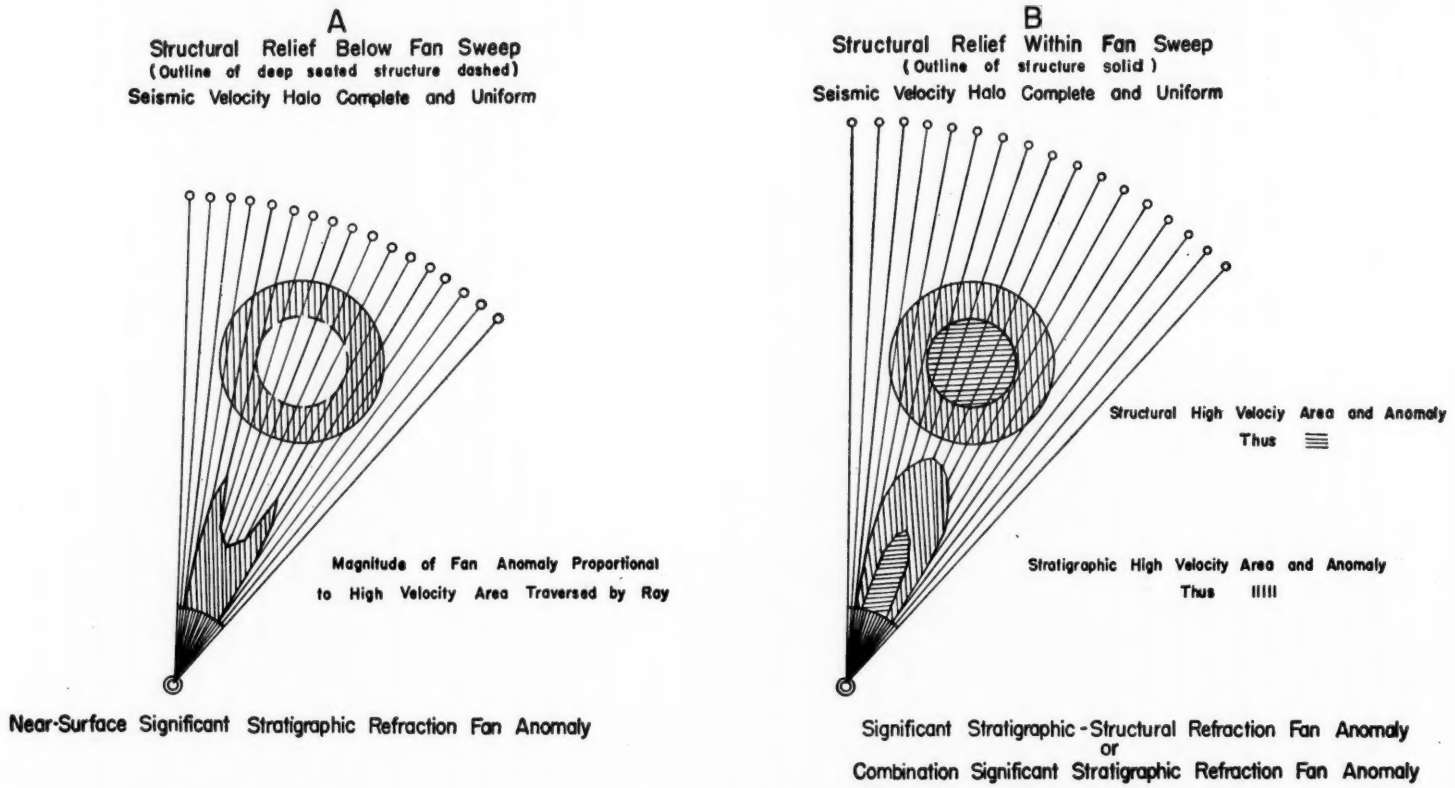

A
Structural Relief Below Fan Sweep
(Outline of deep seated structure dashed)
Seismic Velocity Halo Complete and Uniform
Magnitude of Fan Anomaly Proportional
to High Velocity Area Traversed by Ray
Near-Surface Significant Stratigraphic Refraction Fan Anomaly
B
Structural Relief Within Fan Sweep
(Outline of structure solid)
Seismic Velocity Halo Complete and Uniform
Structural High Velociy Area and Anomaly
Thus
Stratigraphic High Velocity Area and Anomaly
Thus
Significant Stratigraphic-Structural Refraction Fan Anomaly
or
Combination Significant Stratigraphic Refraction Fan Anomaly

FIG. 5. Refraction fan travel-time anomalies for the general case, non-structural hypothesis. A. Structural relief below fan sweep. B. Structural relief within fan sweep.

5. If the deeper survey does intercept an underlying lithologic and/or a near-deposit, significant stratigraphic anomaly, a significant anomaly should be observed. The type of that observed anomaly would be determined by the nature of the originating lithologic anomaly intercepted at depth.

Thus, in the case of stratigraphic petroleum accumulation, the intercepted anomaly would be "combination" significant stratigraphic, i.e., involving the effect of not only the near-deposit but also the near-surface significant stratigraphic variations in lithology. If the near-deposit significant stratigraphic anomaly lies well below the top of the lithologic structure, and so is not intercepted by the survey, the observed anomaly, due to the interception of both the lithologic structure and the near-surface significant variation in lithology, should be stratigraphic-structural. Obviously, various combinations of interceptions of both lithologic structure and significant stratigraphic variations in lithology are possible.

A. However, all of these possible varieties of interception which may be added by the deeper survey should have the same net effect, to reduce the magnitude of the central depression in the seismic velocity structure intercepted by and observed on the shallow survey, i.e., to reduce, eliminate or invert (to a central maximum) the central minimum observed on the shallow survey. Consequently, the configuration of the observed anomaly may be any configuration on a gradation from a double-peaked maximum through a flat-topped (or even triple-peaked maximum) to a single-peaked maximum.

B. If that observed anomaly is a single-peaked maximum, the maximum lead should be properly oriented with respect to the surface projection of the intercepted lithologic structure and/or the near-deposit significant stratigraphic variation in lithology.

6. Thus, as the survey depth increases, a change in *configuration* of the observed anomaly may take place, from a double-peaked maximum (for which the maximum leads are properly oriented with respect to the edge of the surface projection of the petroleum accumulation) towards, or even to, a single-peaked maximum (for which the maximum lead should be properly oriented with respect to the surface projection of the intercepted area of the lithologic structure and/or the intercepted area of the near-deposit significant variation in primary lithology).

RECAPITULATION

In the Gulf Coast refraction campaign of 1924–1931, the primary objective was lithologic structure which was oval or subcircular in cross section.

The referent for describing structural relief was the effective depth of penetration of refraction surveys.

As a result of subsequent development, we now know that intermediate- and low-relief structure, with such a cross section, existed in association with petroleum accumulation.

Thus, utilizing available refraction surveys, a test of the non-structural hypothesis can be based on the following corollaries.

1. Refraction fan anomalies should have been observed which were forbidden by the then and now accepted structural hypothesis.

2. Such structurally forbidden refraction anomalies should be recognizable by one, or more than one, of the following characteristics (none of these, singly or in association, were anticipated in resolution by the structural hypothesis).

A. Observable magnitude when the effective depth of the refraction survey was such as to intercept only low- or negligible-relief lithologic structure.

B. Unique configuration, a double-peaked maximum instead of a single-peaked maximum.

C. Peculiar orientation of maximum leads; these should bracket the outline of the surface projection of petroleum accumulation, rather than be structurally oriented.

D. Change in *configuration* of anomaly with increasing depth of survey, (from a double-peaked maximum towards, or even to, a single-peaked maximum) instead of a change in *absolute magnitude* (from no anomaly to an observable anomaly).

OBSERVED REFRACTION FAN ANOMALIES

Elegant Conditions for the Proposed Critical Test

The proposed critical test is based upon an identification of the structurally forbidden, near-surface, significant stratigraphic refraction anomaly by means of the unique characteristics postulated by the non-structural hypothesis. The elegant method for conducting such a test would be a refraction survey, utilizing refraction fans exploring to increasing depths and properly positioned, across a typical Gulf Coast lithologic structure with the following characteristics.

A. Associated with conformable petroleum accumulation,

B. At a depth comparable with but somewhat less than the maximum depth of effective penetration for refraction prospecting, and

C. Overlain by an appreciable thickness of lithology which is structurally undisturbed within the limits of observational error for refraction prospecting.

Under such conditions, the following alternative results should follow.

Structural Hypothesis Valid

Shallow Survey

On those fans with an effective depth of penetration less than the thickness of structurally undisturbed lithology, no refraction anomaly should be observed.

Deep Survey

On those fans with an effective depth of penetration greater than the thickness of structurally undisturbed lithology, a significant structural refraction fan anomaly should be observed because of the interception of a seismic velocity structure conformable with the lithologic structure. That significant structural

anomaly should be a single-peaked maximum, properly oriented structurally, i.e., the maximum lead should be observed on that seismic ray which has the maximum intercept of the lithologic structure. The area over which that refraction anomaly is observed should be comparable with the surface projection of the cross section of the structure at the effective depth of penetration of the refraction survey.

Non-Structural Hypothesis Valid

Shallow Survey

On a refraction fan, with an effective depth of penetration less than the thickness of structurally undisturbed lithology overlying the structure, a near-surface, significant stratigraphic anomaly should be observed. That structurally forbidden anomaly should have other unique characteristics. Thus, it should be a double-peaked maximum with maximum leads which bracket the surface projection of the petroleum accumulation, and a central minimum which is properly oriented with respect to the petroleum accumulation (i.e., the central minimum lead occurs on that seismic ray which has the maximum intercept of the surface projection of the petroleum accumulation). The area over which that double-peaked maximum is observed should be appreciably greater than the area of the surface projection of the petroleum accumulation.

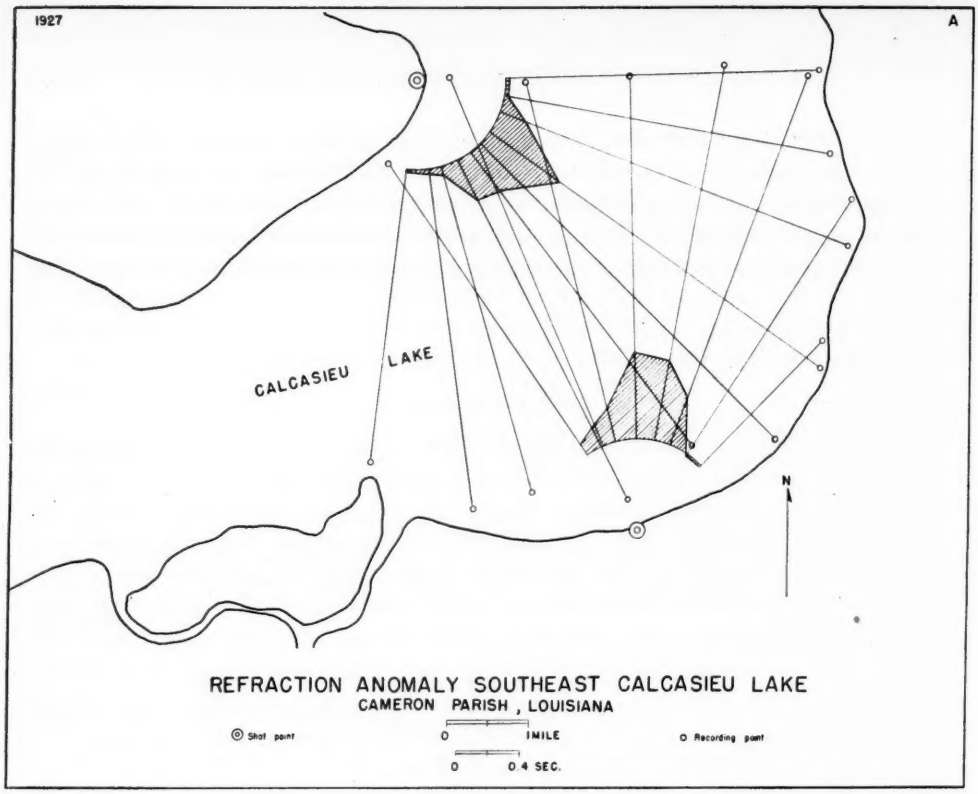
Deep Survey

On a fan with an effective depth of penetration greater than the thickness of the structurally undisturbed lithology overlying the structure, a significant stratigraphic-structural anomaly should be observed. That anomaly may be a single-peaked maximum, properly oriented structurally, i.e., the maximum lead may be observed on that seismic ray which has the maximum intercept of the surface projection of the cross section of the structure intercepted by the refraction fan. However, the area over which that significant stratigraphic-structural anomaly is observed should be greater than the area of the surface projection of the petroleum accumulation, and so greater than the surface projection of the structure at the effective depth of penetration of the refraction survey.

Available Conditions for the Proposed Test

The available conditions for the proposed critical test fell appreciably short of the elegant conditions described in the foregoing paragraphs. Thus, any conclusions reached can be considered only as a measure of substantiating evidence, and not as definitive.

The selection of the case treatments shown in Figures 6–10 was made on the following basis. Available refraction fans were reviewed in the light of established subsurface conditions; particular attention was paid to those for which the revealed structural relief would be classified as intermediate or low at the (estimated) effective depth of penetration for the refraction survey. From these, in-



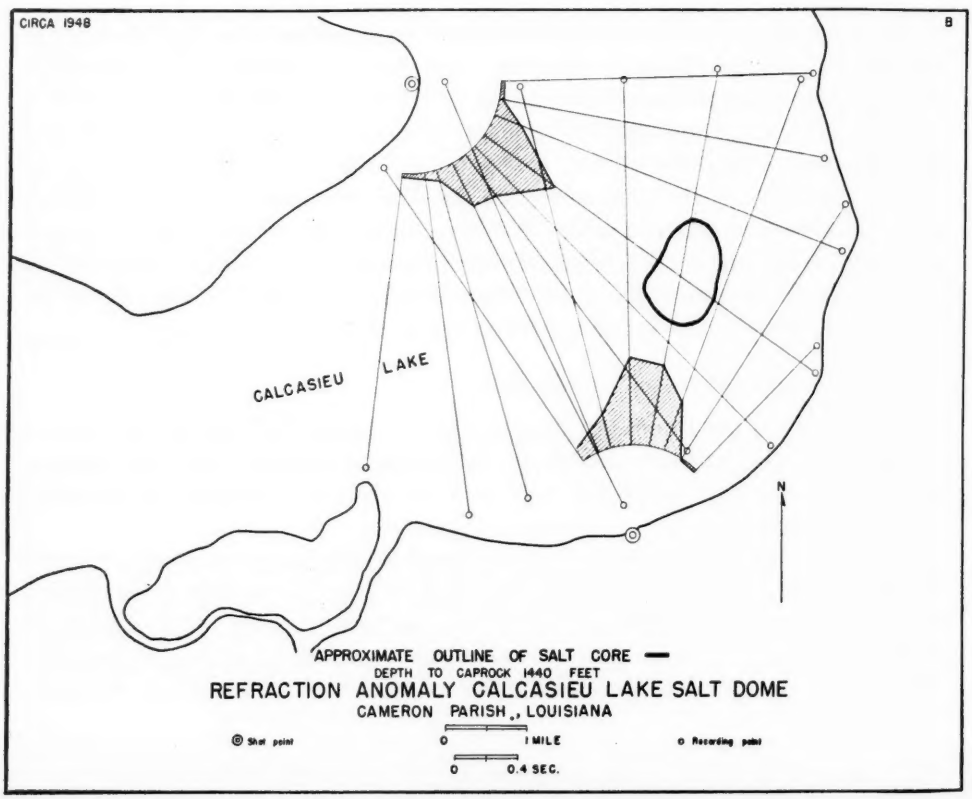


FIG. 6. Refraction fan anomaly, Calcasieu Lake salt dome. A. Prior to discovery. B. Showing outline of salt plug.

stances were selected where the obvious conclusions on the basis of the structural hypothesis differed, in material degree, from the revealed subsurface conditions.*

These refraction fan anomalies are shown just as they were when formally submitted after the completion of the refraction survey, either immediately or as a refraction review interpretation circa 1929–1931, when the graphical presentation of refraction fan anomalies had become standard practice. There has been no subsequent review interpretation of the refraction records, travel-time plots, or report maps. From the standpoint of this study, the refraction anomalies shown can be considered as quite objective since, at the time when their magnitudes and configurations were determined (by technologists considered, at the time, as competent), the non-structural hypothesis under examination had not been conceived.

Each case treatment is shown in two parts, "A," with the extent of development at or shortly after the completion of the refraction survey, and, "B," with the subsequent development to recent date added.

Another case treatment (Cameron Meadows) has been taken from the recent literature, and is interesting because the data from several refraction surveys to different depths can be compared with the subsurface conditions revealed by subsequent development.

The locale for each of these case treatments is in the Louisiana Gulf Coast, except for the Turtle Bay oilfield, which is in the Upper Texas Gulf Coast.

General Description of Case Treatments

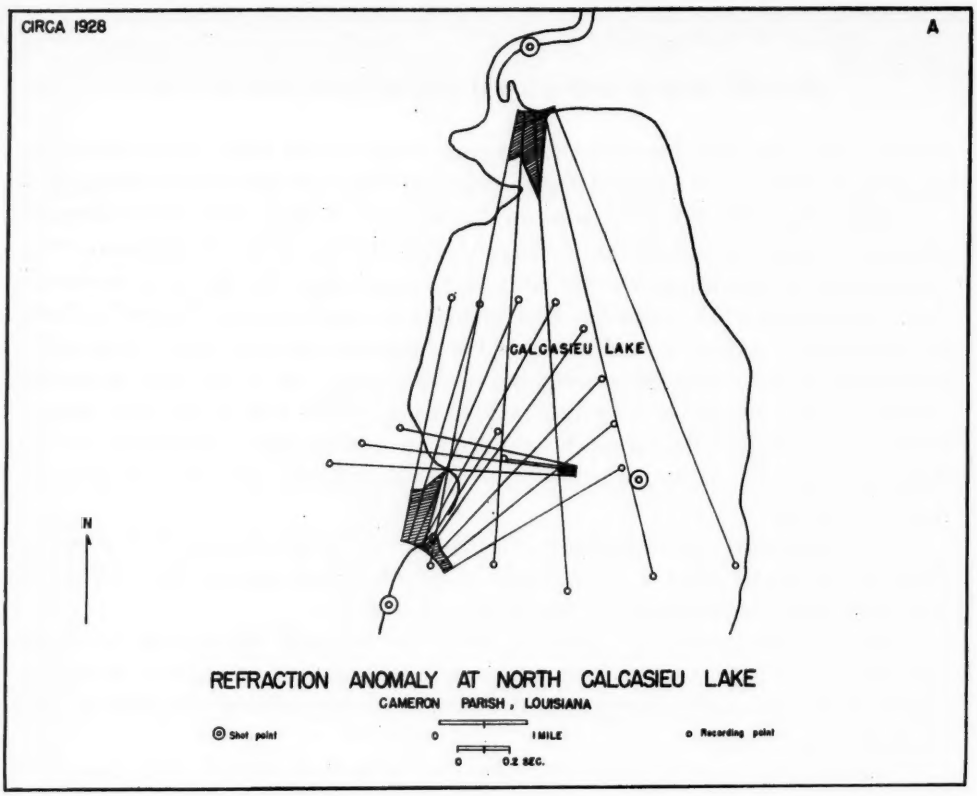
The first case treatment (Calcasieu Lake, Figure 6) is a typical refraction confirmation (and is included herein for comparison with those case treatments wherein resolution by the structural hypothesis proved to be inadequate). The configuration of the observed refraction fan anomalies is a single-peaked maximum of appreciable magnitude, which was found to have been properly oriented structurally. (Subsequent development revealed the presence of a shallow, piercement-type salt dome, verifying the predictions made on the basis of the structural hypothesis.)

The other case treatments differ in that subsequent development revealed subsurface conditions which were not in accord with those predicted or anticipated on the basis of the structural hypothesis. All of these other case treatments are instances where intermediate- or low-relief structure was found to be associated with petroleum accumulation. The following classifications are descriptive.

In one instance (East Hackberry, Figure 7), the configuration of the observed refraction fan anomalies is a single-peaked maximum which, as revealed by subsequent development, was not properly oriented structurally.

In three instances (Turtle Bay, Figure 8, Leeville, Figure 9, and Jeanerette,

* As pointed out in the previous study, the only merit in the nonstructural hypothesis lies in a more adequate resolution of those geophysical failures which followed from resolution on the basis of the structural hypothesis.



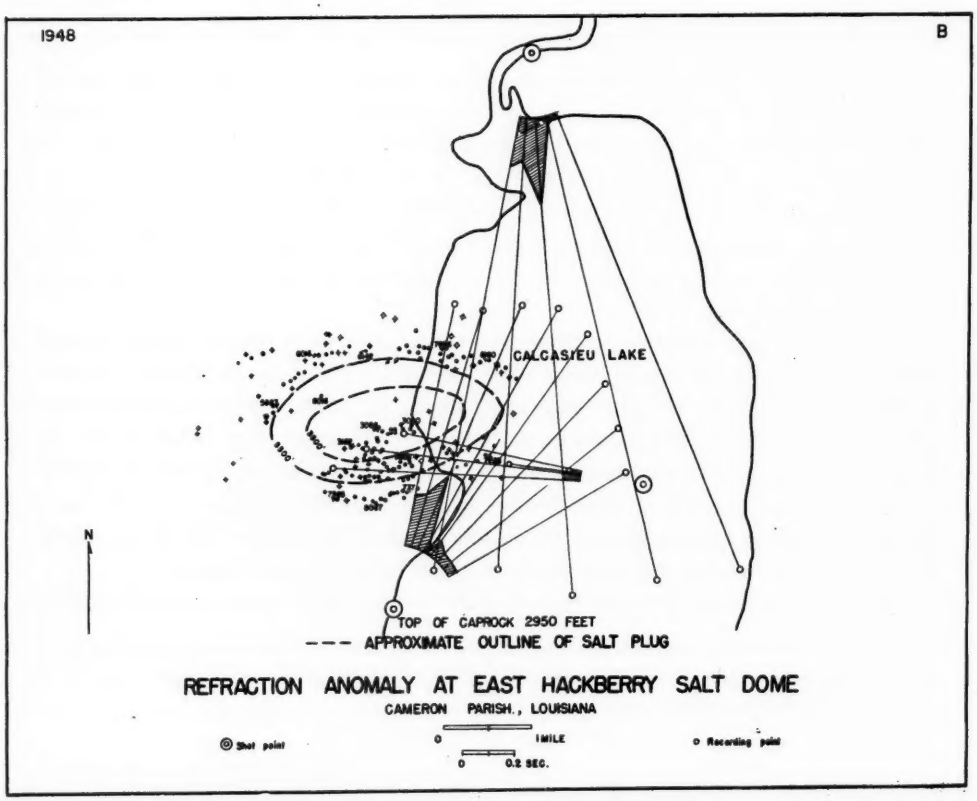


FIG. 7. Refraction fan anomaly, East Hackberry salt dome. A. Prior to development. B. Showing development through 1948.

Figure 10), the observed refraction fan anomalies appear to be structurally forbidden. In the case of Turtle Bay, the (revealed) subsurface relief should have been negligible at the effective depth of penetration of the refraction survey, and, while the magnitude of the observed anomaly was low, it was not properly oriented structurally. At Leeville and Jeanerette, the trace of the recording points crossed the surface projection of the (subsequently discovered) petroleum accumulation, and the underlying structure was below the refraction mirage at the recording points.

In three instances (Leeville, Figure 9, Charenton and Jeanerette, Figure 10), the configuration of several refraction fan anomalies is a double-peaked maximum, with an orientation in accord with that postulated by the non-structural hypothesis. That is, the maximum leads tend to bracket, and the central minimum tends to be properly oriented with respect to, the surface projection of the (subsequently discovered) petroleum accumulation.

In the last case treatment (Cameron Meadows), the initial refraction data, from relatively short profiles, apparently showed the presence of shallow lithologic structure which, in magnitude of relief and areal extent, is difficult to reconcile with the subsequently revealed subsurface conditions. A refraction fan resulted in the recognition of a double-peaked maximum anomaly with an orientation which was found to be reasonably close to that postulated for the typical near-surface significant stratigraphic anomaly. The refraction fans with the greatest effective depth of penetration resulted in more or less typical significant structural anomalies, with maximum leads which apparently were reasonably well oriented structurally.

A more detailed discussion of each case treatment follows.

CALCASIEU LAKE SALT DOME (FIG. 6)

Figure 6A shows a refraction fan anomaly observed on cross fans in southeast Calcasieu Lake circa 1927. On both fans, the configuration of the observed anomaly is a well defined, single-peaked maximum of appreciable magnitude (i.e., leads up to 0.5 second). Salt velocity was observed on each of several profiles shot across the anomalous area prior to development.

On the basis of the structural hypothesis, this refraction anomaly was interpreted as due to a shallow, piercement type salt dome. Its areal extent and position were expected to correspond reasonably well with the area common to the shot-recorder rays with the greater leads.*

Subsequent development resulted in the discovery of a shallow salt dome (caprock was found at 1,445 feet), with an outline approximately as shown in Figure 6B. No commercial production has been established as yet. The revealed

* These fan data were not relied upon for the exact position of the salt core, for the fans were regarded as purely reconnaissance in nature, and the recording positions in the lake had not been permanently marked. A more reliable location of the salt core was made later from controlled, detail exploration.

subsurface conditions were considered to be in satisfactory agreement with those predicted, on the basis of the structural hypothesis, from the refraction data. (Similar agreement would have resulted had the resolution been made on the basis of the special structural sub-hypothesis.)

EAST HACKBERRY SALT DOME AND OILFIELD (FIG. 7)

At the time that this refraction survey was made (by a water-borne refraction crew), the presence of a salt dome in the immediate vicinity was known from land refraction surveys. The immediate problem was whether and the extent to which that salt dome extended under Calcasieu Lake.

The observed refraction anomalies are shown in Figure 7A, one from the northern shotpoint and a second from the southern shotpoint. These refraction fan anomalies have the same configuration, a maximum lead associated with two intermediate leads, and are almost mirror images of each other. Since, in each case, the easternmost lead is the largest, the configuration appears to be that of an asymmetric, single-peaked maximum.

On the basis of the structural hypothesis, such a configuration was expected to result from an underlying lithologic structure (i.e., the salt dome) with its largest dimension on its eastern edge and narrowing to the west, the direction in which the leads decrease.

Figure 7B shows the results of subsequent development, revealing not only that the actual extent of the salt core (under the lake, and at depths within the effective penetration of the refraction fan sweeps) fell short of that anticipated, but also that its cross section widens rather than narrows to the west. Caprock was found at 2,950 feet. Commercial production has been established around much of the periphery of the salt plug, as shown in Figure 7B.

If the observed refraction anomalies are considered from the standpoint of the non-structural hypothesis with reference to their meaning in terms of the revealed subsurface conditions, the following points can be made for both.

1. The easternmost lead is the greatest.

2. However, the fan was not swung far enough to the west to secure coverage off the anomaly, for the westernmost shot-recorder ray still shows an appreciable lead.

3. Thus, the configuration of the fan anomaly may well be that of an incomplete double-peaked maximum, such as that which would have resulted if the fan in Figure 5A had been similarly restricted.

4. If such is the case (i.e., that the configuration actually is that of an incomplete double-peaked maximum rather than that of an asymmetric single-peaked maximum), then the presence of a seismic velocity halo was indicated, potentially significant with respect to petroleum accumulation.*

* In this case treatment, the maximum lead on each anomaly (i.e., the easternmost) appears to be properly oriented with respect to the subsequently discovered flank petroleum accumulation. This contradiction of the special stratigraphic hypothesis may be explained as follows.

If one dimension of the petroleum accumulation is several times the other (and this latter is

Thus, if the refraction fan anomalies in Figure 7A are designated as "structural" anomalies and resolved by the structural hypothesis, the conclusions dawn (as to shape and areal extent of the postulated lithologic structure) differ materially from the actual subsurface conditions. On the other hand, if recognized as near-surface significant stratigraphic anomalies and resolved by the special stratigraphic sub-hypothesis of the non-structural hypothesis, then the resulting conclusions are in much closer accord with the actual subsurface conditions.

TURTLE BAY OILFIELD (FIG. 8)

Figure 8A* shows a refraction fan anomaly which, circa 1930, was observed, recognized as marginal, and put on the shelf for later possible consideration.

On the basis of the structural hypothesis, such a marginal, flat-topped maximum refraction anomaly presumably had an origin in a low-relief lithologic structure, located somewhere under those shot-recorder rays on which the leads were observed.

Figure 8B shows the results of independent, subsequent development. A low-relief, deep-seated structure does exist in the area, with approximately conformable petroleum accumulation.

With respect to the depth and relief of the revealed subsurface structure, the predictions on the basis of the structural hypothesis were satisfactory. However it is evident that the observed flat-topped maximum is not properly oriented structurally, but, rather, is just "off the beam" in that respect. A test well located on the basis of the structural interpretation of that flat-topped maximum refraction anomaly very probably would have been, at best, a lateral miss, and so charged off as a refraction failure.

Subsequent development thus indicates that the Turtle Bay refraction anomaly did not result from interception of the revealed lithologic structure by the refraction fan sweep. On the other hand, its configuration is not the double-peaked maximum postulated by the stratigraphic hypothesis. The explanation

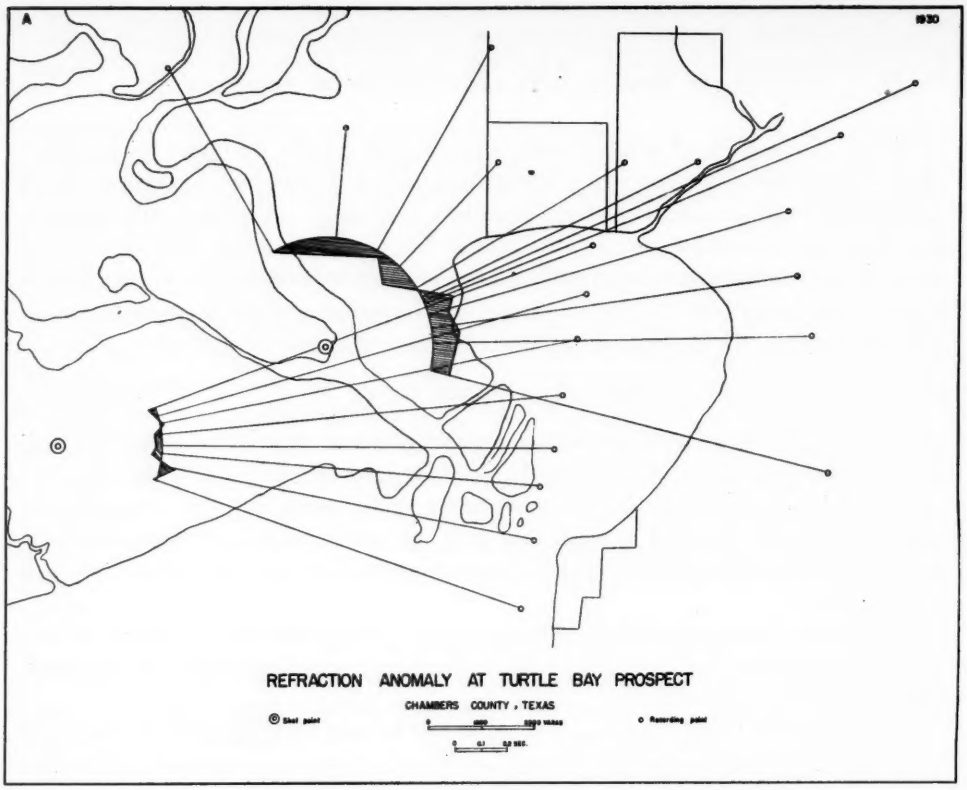
small), the usual refraction fan shot along the greater dimension may not be able to resolve the closely spaced double seismic velocity halo postulated by the special stratigraphic hypothesis. The result would be a refraction *maximum* apparently properly oriented with respect to petroleum accumulation.

Inspection of Figure 7 shows that, while the configurations of the anomalies shown on the northern and southern shot points are approximate mirror images of each other, the maximum leads are not oriented towards a common center of anomaly.

As was mentioned in the case treatment of the Calcasieu Lake salt dome (Fig. 6), fan data such as these were considered as reconnaissance in nature. The recording positions were surveyed in to the shot point with distances from air wave travel-times and bearings by hand compasses, and to adjacent recording boats with the latter only; they were not marked for permanent record.

In the light of such field practice, at the time considered adequate for the solution of the problem at hand, the writer recommends that little emphasis be placed upon the "disagreement" in orientation of these maximum leads. That "disagreement" may be real or only apparent; the data at hand were not taken with that point in view, and do not permit solution of that question.

* Figure 8B, without the structural contours, was included as Figure 4, p. 1410, in "Geochemical Prospecting For Petroleum," *Bull. Amer. Assoc. Petrol. Geol., Vol. 24* (1940), 1400–1433.



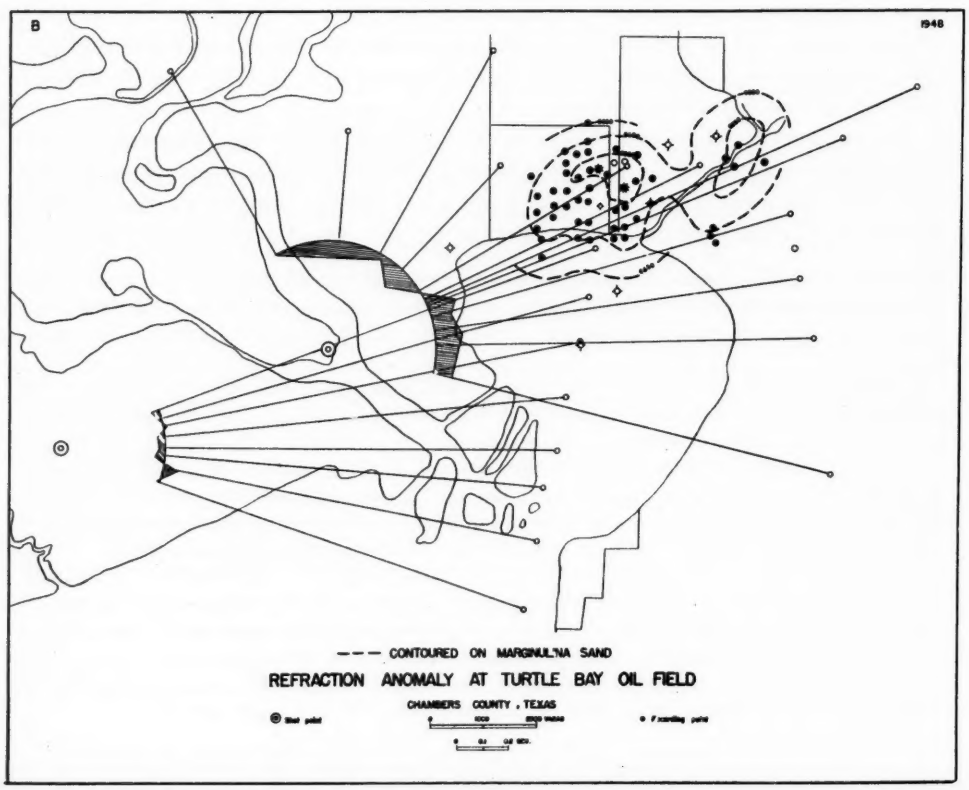


FIG. 8. Refraction fan anomaly, Turtle Bay oilfield. A. Prior to discovery. B. Showing development through 1948.

proffered in the case of East Hackberry (Fig. 7) can hardly apply here, for the Turtle Bay refraction fan *was* swung to the west of the subsequently revealed structure.

The explanation is believed to lie in the lengths of the shot-recorder lines. Those to the west of the oilfield, which should show the other half of the (postulated) double-peaked maximum, are much shorter than the shot-recorder lines which did show leads. Experience in refraction prospecting indicated the advisability of having the same, or nearly the same, length for all shot-recorder lines, for thereby the determination of the normal travel-time relationship was materially facilitated.

The refraction anomaly observed at the Turtle Bay oilfield, then, is another case treatment where the non-structural hypothesis is more useful in reconciling an observed refraction anomaly with (subsequently revealed) low-relief structure associated with petroleum accumulation, for the attempt to resolve this particular anomaly by the structural hypothesis certainly would have led to misleading conclusions, which, if tested by the drill, might well have resulted in a refraction failure.

LEEVILLE SALT DOME AND OILFIELD (FIG. 9)

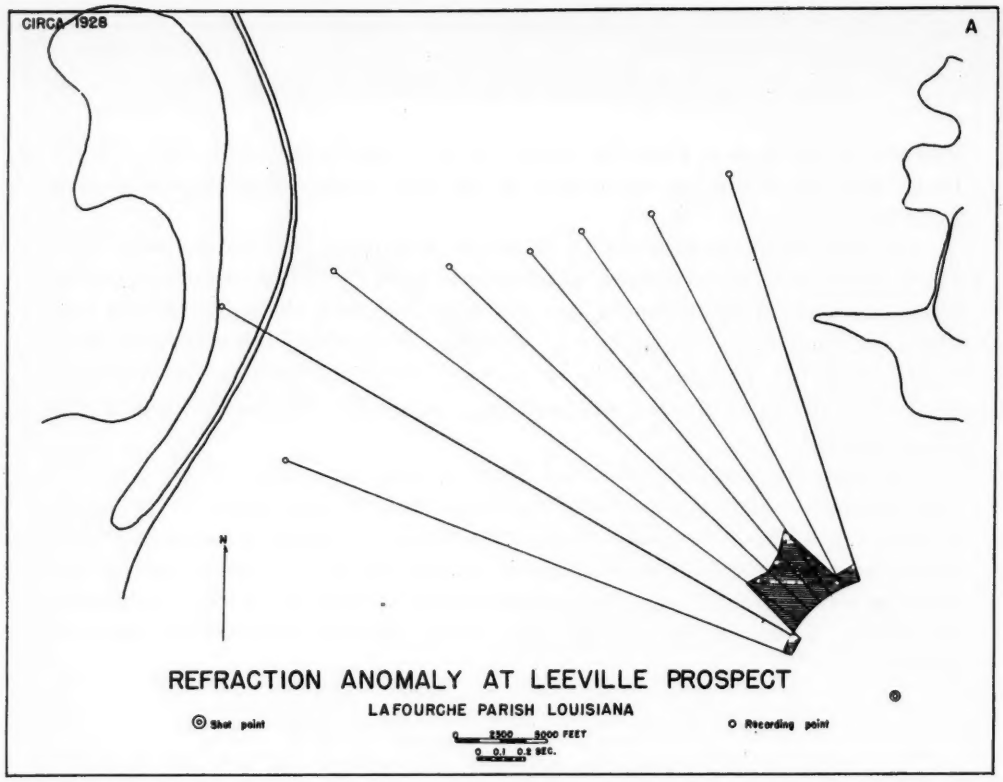
Figure 9A shows a refraction anomaly observed at the Leeville area circa 1928, with its configuration that of a double-peaked maximum.

If resolved by the structural hypothesis, a reasonable conclusion would be that such an anomaly resulted from the interception of a (lithologic) structure either with a somewhat dumbbell shaped outline, or with a depression in the center (similar to a central graben). The magnitude of the leads was such (0.2–0.3 second) as to suggest an intermediate-depth structure rather than a shallow salt plug. If that were the case, the intercepted area of the lithologic structure should have been located at or reasonably close to the mid points of the shot-recorder rays on which the leads were observed. On the other hand, if the intercepted area of the structure was not at those mid points, then its depth had to be correspondingly less, for the closer to the shot or recorder point, the shallower the effective penetration of the fan sweep.

Figure 9B shows the result of subsequent development, revealing the interesting situation that the trace of the recording points passed directly over a subsequently discovered salt dome, associated with petroleum accumulation, on which caprock was found at a depth of 3,789 feet.

On the basis of the structural hypothesis, the observed refraction anomaly can hardly be reconciled with the revealed subsurface conditions, in fact, is "forbidden." An intermediate-depth salt dome which lies under the so-called refraction "mirage" (postulated under the shot and recorder points) should have been below the sweep of the refraction fan, and so no refraction fan anomaly should have been observed.

On the other hand, this refraction fan anomaly can be resolved quite satis-



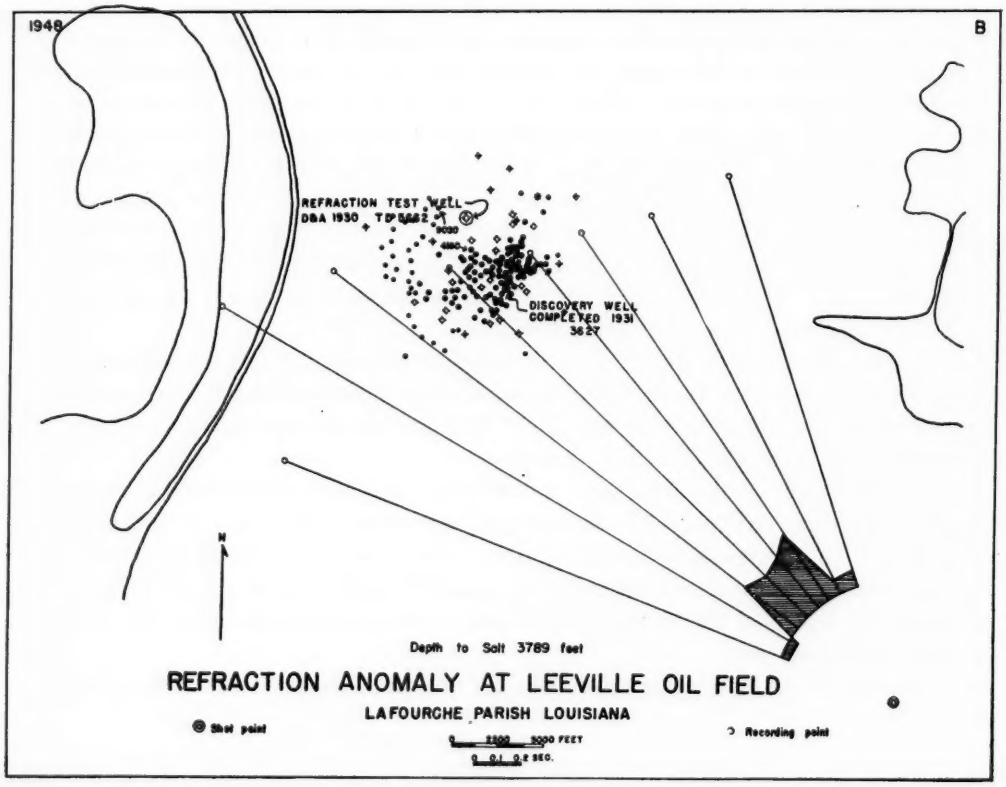


FIG. 9. Refraction fan anomaly, Leeville salt dome and oilfield. A. Prior to discovery. B. Showing development through 1948.

factorily by the stratigraphic hypothesis. Since petroleum accumulation was present (as revealed by subsequent development), a seismic velocity halo should have existed around the near surface projection of the limits of petroleum accumulation. A seismic velocity halo can be drawn in Figure 9B which would account, reasonably well, not only for the refraction anomaly itself, but also for its observed configuration.

Here, too, there appears to be more justification for classifying the Leeville refraction anomaly as a near-surface significant stratigraphic anomaly (and resolving it by the non-structural hypothesis) than there is for classifying it as "structural" (and resolving it by the structural hypothesis).

CHARENTON AND JEANERETTE OILFIELDS (FIG. 10)

Figure 10A shows the refraction anomalies observed circa 1930 in the Charenton-Jeanerette area. Two anomalous localities were recognized, the more outstanding to the east known as Charenton, and the other, to the west, as Jeanerette. Of the two, the Charenton prospect was considered as the more promising, not only because the refraction anomaly there was more outstanding, but also because favorable surface indications had been found on the nearby shores of Grand Lake.

Refraction profiles across the Charenton refraction anomaly did not show salt velocity. Although the magnitude of the leads was small (0.1–0.2 second), the record quality was satisfactory, and the leads grouped so as to indicate a localized refraction anomaly with an appreciable areal extent.

On the basis of the structural hypothesis, a test well location was recommended in the immediate vicinity of the intersection of the maximum leads. As shown in Figure 10A, this test well was abandoned as dry at 7,850 feet, a refraction failure.

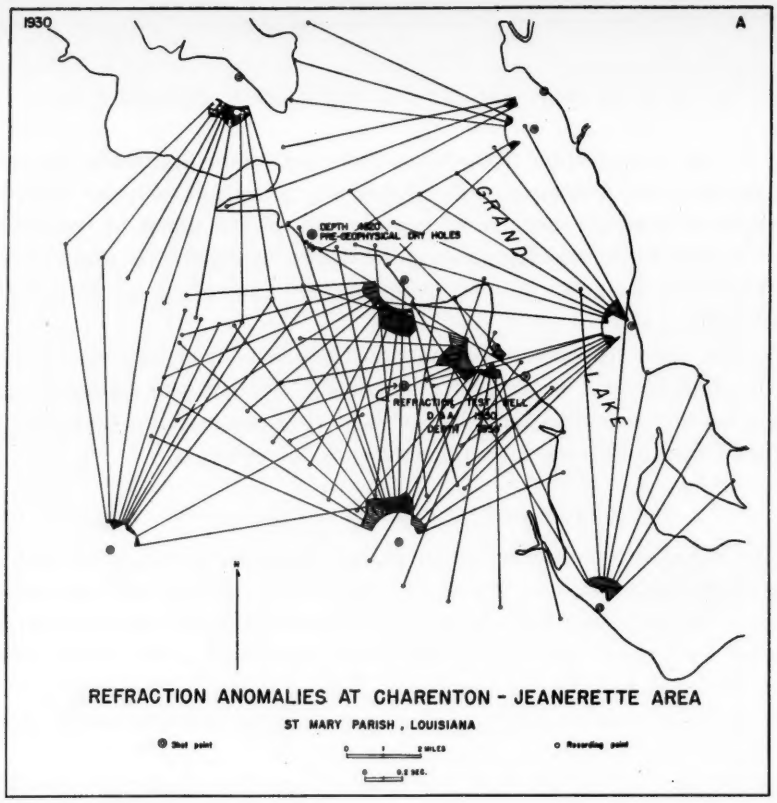
Figure 10B shows the development in the area through 1948. Note how the productive area at Charenton is bracketed by the maximum refraction leads, so that the refraction failure, located on the basis of the structural hypothesis, now is shown to have been a lateral miss of petroleum accumulation.

To the west, at Jeanerette, the maximum leads also bracket subsequently discovered petroleum accumulation, for which the central minimum lead was properly oriented.

Note also, at Jeanerette, how the trace of the recording points for the northern shot point runs across the (subsequently) productive area, indicating that here, as at Leeville, the structure lies within the refraction mirage. Hence the leads observed from the northern shot point also result from a structurally forbidden refraction anomaly.

As yet, salt has not been reached at Charenton, but has been found at Jeanerette at a depth of 10,314 feet.* Thus, from the standpoint of refraction pros-

* Personal Communication, O. C. Clifford, Jr.



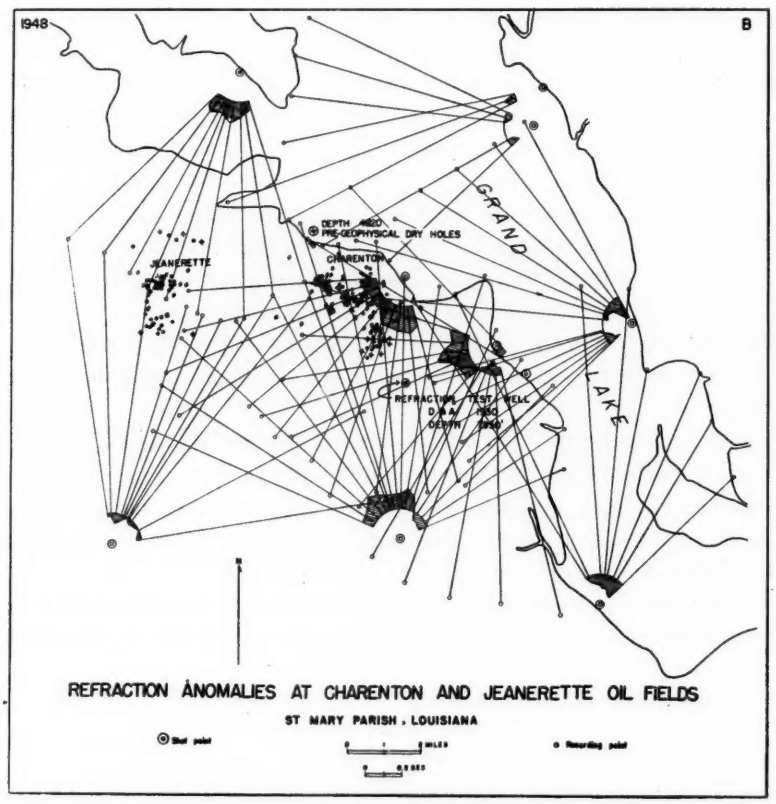


FIG. 10. Refraction fan anomalies, Charenton and Jeanerette oilfields. A. Prior to discovery. B. Showing development through 1948.

pecting, both areas represent low-relief structure associated with petroleum accumulation.

On the basis of the structural hypothesis, then, if refraction anomalies were observed under such structural conditions, the leads should have been, at best, marginal in magnitude, and the configuration of the fan anomalies (if observed) that of a single-peaked maximum, properly oriented structurally.

Actually, refraction anomalies were observed, with leads small but hardly marginal. Further, the typical configuration is that of a double-peaked maximum, with the *central minimum* properly oriented with respect to petroleum accumulation; as for the maximum leads, they tend to be properly oriented with respect to limiting dry holes.

Here, again, the observed refraction anomalies can be more adequately resolved on the basis of the non-structural hypothesis than they were, *or could be today*, resolved on the basis of the structural hypothesis.

CAMERON MEADOWS OILFIELD

The case history of the Cameron Meadows oilfield* is rich in the amount of geophysical information presented and in the opportunity to compare the data with the subsurface lithologic structure revealed by subsequent development.

Of the various refraction surveys which are described in that case history, the shallowest was that conducted by the Seismos, G.M.B.H., in 1926. This is described as follows (p. 164).

"The length from shot point to detector was from $1\frac{1}{2}$ to 4 miles, averaging about 3 miles, distances being carefully obtained by surveying crews. It is of interest to note that, from theoretical considerations, they felt sure no additional penetration was obtained by shooting distances greater than $3\frac{1}{2}$ miles."

Since the Seismos interpreters "did not submit a detailed map of the results, only a map showing tent (recording) and shot point distances and lines joining shot point to recording locations" (pp. 164–165), a critical review of the data is impossible. Such a review, made in the light of the revealed subsurface conditions, might establish whether or not this first seismic survey did intercept an underlying lithologic structure. Presumably the Seismos interpreters were not sure on this point, for "in the conclusions to their report they say

'the region around the shell hill in T 14 S, R 13 W, cannot be called fully normal: there may be a possibility to find a structure in Sections 21 and 28 of this region.'" (p. 164).

Figure 2, p. 164, is a reproduction of a "Seismos Company dip indication map," which shows 300 feet of south dip in a distance of about $1\frac{1}{2}$ miles over a depth range of 1,600 to 1,900 feet. Presumably Figure 2 purports to show the

* G. M. McGuckin, "History of the Geophysical Exploration of the Cameron Meadows Dome, Cameron Parish, Louisiana," *Geophysical Case Histories, Vol. I*, Society of Exploration Geophysicists (1948), pp. 161–174. (In this writer's discussion of the Cameron Meadows oilfield, figure and page references are to those in that published case history.)

lithologic structure postulated from the refraction profiling. Apparently a refraction anomaly was observed in that early, shallowest refraction survey, for the indicated (lithologic) subsurface conditions shown on that map certainly are abnormal. On the basis of the structural hypothesis, such an observed refraction anomaly indicated that an underlying, local lithologic structure had been intercepted. Certainly the Seismos interpreters inferred if they did not actually indicate that structural interception.

It happens that this refraction contour map cannot be properly evaluated even today, for the lithologic structure above the salt cannot be worked out even from electric logs of drilled wells. However, on the basis of the structure as revealed on the salt (Figure 7, p. 168), and from what is known of supra-salt structure under similar conditions elsewhere, the existence, magnitude and areal extent of the shallow (lithologic) structure depicted in Figure 2 are, to say the least, surprising, even questionable.

In Figure 4, p. 166, the refraction fan data are shown from three Geophysical Research Corporation surveys. Since the recorder positions are not shown on that map, the full significance of the anomalies cannot be determined therefrom. However, note that the refraction fan anomaly associated with SP 9 is a double-peaked maximum, outstanding in areal extent, and with maximum leads apparently more than half as great as any others shown.

The westerly peak of this double-peaked maximum apparently is properly oriented with respect to the subsurface lithologic structure, i.e., the structural apex on the salt (Fig. 7, p. 168). On the basis of the structural hypothesis, and particularly in view of that apparent confirmation of structural resolution, there should be a comparable lithologic structure associated with the other, easterly peak of that refraction anomaly. No such lithologic structure, however, is indicated either by the available subsurface information or by the reflection data which (Fig. 6, p. 168) cover the area where this second lithologic structure should be located.

Again, if this double-peaked maximum refraction anomaly is due to subsurface lithologic structure, investigation with greater penetration (i.e., longer shot-recorder distances) should have resulted only in an accentuation of the anomaly observed on the shallower survey. However, even though longer shot-recorder distances were used in the later refraction exploration, in no case did the configuration of any of the resulting refraction fan anomalies confirm the double-peaked maximum previously observed at SP 9; this should have happened if that anomaly originated wholly in lithologic structure.

Thus, at Cameron Meadows, the structural interpretation of the refraction data appears to be inadequate on three counts, as follows.

1. The existence, magnitude and areal extent of the shallow lithologic structure (apparently mapped in the Seismos profiling) is open to question in the light of known characteristics of similar salt structures.

2. While the westerly peak of the double-peaked maximum anomaly ob-

served from SP 9 appears to be properly oriented with respect to lithologic structure (i.e., apex of the salt), there is no evidence for the existence of any similar *lithologic* structure associated with the easterly peak of that outstanding refraction anomaly.

3. Later refraction fans with greater depths of effective penetration did not confirm the earlier recognized double-peaked maximum; only (approximately) single-peaked maxima were observed.

On the other hand, resolution of these refraction data on the basis of the non-structural hypothesis appears to be reasonably adequate, as follows.

1. The existence, areal extent and magnitude of the shallow *seismic velocity* structure mapped by the Seismos profiling is reasonable in terms of a near-surface significant stratigraphic anomaly originating in stratigraphic variations in primary lithology associated with (subsequently discovered) petroleum accumulation. That is, the contours shown in Figure 2 probably are contours on the outer, southwestern edge of a *seismic velocity* structure, not necessarily on a shallow, *lithologic* structure.

2. The double-peaked maximum observed from SP 9 is a typical refraction expression of a near-surface, significant stratigraphic anomaly anticipated across low-relief Gulf Coast structure associated with petroleum accumulation; those subsurface conditions were revealed at Cameron Meadows by subsequent development. Thus, the double-peaked maximum observed from SP 9 confirms the *seismic velocity* structural contours in Figure 2 which resulted from the Seismos profiling. The apparent (lithologic) structural orientation of the westerly peak of that double-peaked maximum is coincidental, for the underlying petroleum accumulation now is known to play out to the west against the apex of the salt structure. The easterly peak of that anomaly does not indicate the existence of another lithologic structural apex, but rather should be the other "bracket" to the surface projection of the petroleum accumulation.

3. The later refraction fans with greater effective depths of penetration should not necessarily have confirmed the double-peaked maximum. If those greater effective depths of penetration resulted in the interception of lithologic structure and/or a near-deposit, significant stratigraphic anomaly, single-, rather than double-, peaked maxima might well have resulted.

In discussing these refraction data, the writer has taken the liberty of introducing the adjective "lithologic" before "structure" where it does not occur in the original context. So far as he knows, that specification was implied and understood in nearly all, if not all, of the refraction interpretation during the Gulf Coast campaign of 1924–1931.

Note, then, that the fundamental difference between resolution by the structural and by the non-structural hypotheses is whether or not that specification (of *lithologic* structure) is made or implied. Thus, the structural interpreter means or implies *lithologic* structure in any otherwise unqualified reference to "structure"; the non-structural interpreter will mean, imply, and should state *seismic*

velocity structure *if that is what he measures*. Even the structural interpreter would agree, after consideration, with the non-structural interpreter that these refraction surveys mapped *seismic velocity* structure, *not lithologic* structure. The basic difference between the two is that the structural interpreter proceeds on the basis of the tacit assumption that seismic velocity structure *is* lithologic structure.* The non-structural interpreter would not make that unconscious, automatic identification of seismic velocity structure with lithologic structure; rather he would proceed, first, to map the local seismic velocity structure, and second, to consider the potential economic significance of that seismic velocity structure in terms of an origin which could be wholly, partly, or other than, lithologic structure.

THE ANOMALOUS ANOMALIES OF THE GULF COAST REFRACTION CAMPAIGN

From time to time, the Gulf Coast seismologists observed anomalies for which there appeared to be no rational interpretation in terms of recognized and accepted potential economic significance. Situations such as these came about as follows.

General agreement prevailed that two characteristics were common to those refraction anomalies with a recognizable potential economic significance. First, the apparent cross section of the observed anomaly should be subcircular or oval, similar to the cross sections of the then known salt domes (the generally accepted primary objective). Second, in view of the element of relative permanence associated with lithologic structure, once an anomaly had been observed on a refraction fan, its latitude and longitude should be only a matter of cross-fanning. That is, the reasonably exact location of an observed anomaly should be definitely ascertainable.

Translated into operational concepts, these criteria postulated that, if leads were observed on a given fan, comparable leads should be observed on a properly positioned cross fan, and that, for a given pattern of cross fans, there should be one, and only one, general center of interest where the maximum leads tended to converge.

The anomalous anomalies failed to meet these criteria. There were two types, the "one way" anomaly and the "rubber" dome.

The "One Way" Anomaly

In the case history of the Darrow dome,† mention is made of a "ridge . . . small in (one) extension"; this was postulated as a result of one of the first refraction surveys of the area (p. 147, q.v.).

* Semantically, such is a "signal reaction; that is, a complete and invariable reaction which occurs whether or not the conditions warrant such action." By contrast, the non-structural interpreter's is a "symbol reaction; that is, a delayed action, conditional upon the circumstances." (S. L. Hayakawa, *Language in Action*, Harcourt Brace and Co., Inc. (1941), p. 27.)

† J. B. Eby, and T. I. Harkins, "The Geophysical History of Darrow Dome, Ascension Parish, Louisiana, *Geophysical Case Histories, Vol. I*, Society of Exploration Geophysicists (1948), pp. 144-152.

Later, the following statement is made (pp. 151–152).

"The fact that refraction shooting showed acceleration in one direction and not in another did not conform to all previous structures, which showed accelerations in all directions. It was not until later, for example, that refraction work over Goose Creek Oil Field showed as much as a one-tenth second acceleration in one direction and none at all in other directions. This is not the place to explain such anomalies, but to report that they do exist over some known structures."

This appears to be a description of the phenomenon occasionally recognized in the Gulf Coast refraction campaign, the "one way" anomaly, for which a definite, reproducible lead picked up on one fan was not observed on a cross fan. (The term "one way" is subject to misinterpretation; it meant "one way, back and forth" and not at right angles. That "one way" was not the equivalent of a "one way" street.) The profile (seismic) velocity along such an anomaly always was less, in the writer's experience, than that characteristic of salt (circa 15,000 feet per second). In addition, the records which showed such "one way" leads did not have the low-amplitude forerunners often observed in the records of those seismic waves which had passed through a salt plug.

The "one way" anomaly was difficult to explain on the basis of the structural hypothesis, since its characteristics could be satisfied only by postulating a long, narrow, ridge-like lithologic structure. Such a structural configuration was quite out of keeping with the usual cross section of known Gulf Coast salt domes; these tended to be subcircular or oval.

On the other hand, the non-structural hypothesis anticipates the possible observation of such a "ridge-shaped" *seismic velocity* structure, for that description certainly fits a refraction fan anomaly resulting from the fan sweep interception of only a segment of a seismic velocity halo.

Conditions approximating a "one way" refraction anomaly are shown in Figure 7 (East Hackberry). There the fans from the north and the south shotpoints showed leads over much the same area, but the cross fan from the east shotpoint, although also across the presumably anomalous area, failed to show leads comparable with those shown on the other two fans. On the basis of the non-structural hypothesis, this "one-way" refraction anomaly can be explained by postulating that the fans from the north and south shotpoints picked up leads because they were oriented along a segment of a seismic velocity halo, but that the cross fan from the east failed to show a lead because it intercepted only the narrower width of that seismic velocity halo.

That is, the non-structural hypothesis explains a "one way" refraction anomaly as one which originates in a "ridge-like" *seismic velocity* structure which is not necessarily conformable with lithologic structure. Such a seismic velocity structure would be observable on a seismic ray which travels along its greater dimension, but would not be observable on a ray which traverses its much smaller width. The potential economic significance of such a "one way" refraction anomaly is that of a near-surface significant stratigraphic anomaly originating in signifi-

cant stratigraphic variations in primary lithology associated with petroleum accumulation.

The "Rubber" Dome

Another unusual phenomenon, observed and discussed in the refraction campaign, was the so-called "rubber" dome. This type of anomalous anomaly, while apparently findable from several directions, appeared to be located in a different position for each particular combination of cross fans. For the structural interpreter, such an anomaly was exasperating, in fact, unrealistic to the point where it rarely, if ever, was made a matter of written record. There was an understandable reluctance on the part of a conscientious structural interpreter to venture a rational diagnosis of such "shifty" phenomena.

In the absence of a refraction case treatment of a "rubber" dome (one which shows these "elastic" properties on a combination of cross fans), the following instances serve as approximate equivalents (in that they illustrate the failure of different refraction surveys to point to a common center of interest).

Lockport Oilfield

The first test well in this area was located near a gas seep just north of the present limits of production, and resulted in a dry hole. The second center of interest, based on an early refraction survey, led to two dry holes, south and southeast of the present limits of production, shortly after the oilfield was discovered. A later refraction survey indicated no center of interest (i.e., no anomaly was found) in the vicinity of the oilfield. A still later refraction survey resulted in the recognition of a third center of interest, and a consequent dry hole, just to the northwest of the present limits of production. Thus, the real center of interest at the Lockport oilfield (the oilfield itself) is positioned between three centers of prospecting interest, no one of which was properly oriented structurally. Two of these off-structural centers of interest are marked by dry holes drilled as a result of refraction survey, and the third by a dry hole drilled on a surface gas seep.

Charenton Oilfield

The first center of interest recognized here was located on the shores of Grand Lake, where the presence of gas seeps and paraffine dirt beds resulted in dry holes north of the present limits of production. A refraction survey (Fig. 10) indicated a second center of interest which led to a dry hole south of the present limits of production.

About the same time, another refraction survey indicated a third center of interest to the west of the present limits of (the then undiscovered) production, on which, however, no test well was then located. Thus, even before the discovery of the oilfield, there was general agreement that the Charenton prospect had merit, but also disagreement as to where the real center of interest actually was. These earlier recognized prospecting centers of interest, a "rubber" dome, if you

will, now are seen to have been off-structurally positioned, in that they were located around, and not too far from, the limits of subsequently discovered petroleum accumulation.

These two instances of "rubber" dome equivalents cannot be adequately explained on the basis of the structural hypothesis, for, obviously, the indicated seismic velocity structures were not conformable with the subsequently revealed subsurface lithologic structure. On the other hand, little difficulty is experienced in resolving them on the basis of the non-structural hypothesis.

Thus, if seismic velocity halos are postulated at Lockport and Charenton, then the isolated and separated refraction centers of interest represented local segments of annular *seismic velocity* structures isolated by particular refraction fan surveys. Such near-surface, significant stratigraphic anomalies are anticipated by the non-structural hypothesis for the case of low-relief structure associated with petroleum accumulation. Since salt has not been found (to date) at either of these two oilfields, they represent low-relief structure in terms of the effective depth of penetration for refraction surveys.

Thus, when viewed in the light of the structural hypothesis (i.e., as seismic velocity structures which *should be* conformable with lithologic structure), the anomalous refraction anomalies were so implausible that little more than a passing reference thereto appears in the refraction literature. On the other hand, when viewed in the light of the non-structural hypothesis (i.e., as seismic velocity structures which *should not, necessarily, be* conformable with lithologic structure), a rational interpretation of their potential economic significance is not only possible, but also plausible.

The writer wishes to thank Mrs. Florene Green and Mr. Ben Journeay for preparing the figures in this study, Mr. Journeay for preparing the subsurface contours at the Turtle Bay oilfield (Fig. 8), and to acknowledge suggestions and constructive criticism from Mr. Carol G. Rosaire, Mr. Donald M. Davis, Mr. Henry Cortes, and Dr. L. W. Blau.

GEOPHYSICAL EXPLORATION OF SOUTHWEST HUNGARY*

RAOUL VAJK†

ABSTRACT

Geophysical exploration of an eight million acre oil concession covering southwest Hungary is discussed. During ten years of exploration (1933–1943), about 20,000 torsion balance, 12,000 gravity meter, and 15,000 magnetometer stations were made, and reflection seismograms were recorded at about 2,500 shot points. As a result of this exploration, four oil pools and a gas pool were discovered and a number of geological structures and major faults were located. Gravity, magnetic, and seismic maps showing most of the geophysical data are submitted. Interpretations of the geophysical results, geological data from subsequent drilling, and a schematic tectonic map of southwest Hungary based on the geophysical surveys are also presented.

I. INTRODUCTION

In 1933 the Hungarian parliament granted an eight million acre oil and gas concession to the European Gas and Electric Company (now owned by the Standard Oil Company (N. J.). This concession covered southwestern Hungary, the area south and west of the Danube as far as the Austrian and Jugoslavian frontiers.

Geologically, this area is the western part of the Pannonian basin (outlined by the Carpathian Mountains) which began to sink during the Tertiary and continues to sink even at the present time.[1] The sinking of the basin was not uniform and some blocks of the former Mesozoic mountain system remained in a relatively high position, forming a range of hills with moderate heights (up to 1,800 feet) striking in a northeast-southwest direction through the center of the area, and two similar island mountains occur in the southeastern part of the area. These are the Bakony Mountains, the Vertes Mountains, the Buda Mountains, and the Mecsek and Villany Mountains respectively. (See Plate 1.)

At and around the southwest end of the Bakony Mountains, small cones of extinct basalt volcanoes are located. Basaltic tuffs and intrusions are common in this part of the area.

In the Mecsek Mountains, trachy-dolerite tuffs, plugs, and dikes of Cretaceous age are present.

Two small granite hills, the Velence and the Fazekasboda Mountains, join the above mentioned Mesozoic mountains. Along the Austrian border, outcropping crystalline schists of Paleozoic (?) age form a mountain ridge which is the western border of the Pannonian basin and separates this basin from the Vienna and Graz (or Steier) basins.

The northwestern part of the concession is flat, being part of the Little Hun-

* Presented at the St. Louis Meeting, April 25, 1951. Manuscript received by the Editor September 21, 1951.

† Standard Oil Company (N. J.), New York.

garian Plains. The rest of the area is moderately hilly and gently rolling country with wide, flat river valleys. Most of the concession (outside of the mentioned Mesozoic and granite mountains) is covered with Recent, Quaternary and Levantine sediments with some Pliocene outcrops. These sediments are without definite stratification and without key beds. Occasionally strong cross-bedding is observed even in the Pliocene strata.[2] Consequently no reliable tectonic observations can be made by surface geological methods except to a limited extent in the southwestern corner of the area, and the exploration had to be carried out mainly by geophysical methods.

In 1933 the gravity meter was not yet developed; therefore the gravity survey was made first with torsion balances, even in the hilly parts of the area. These areas were later resurveyed with the gravity meter.

Most of the concession was covered with a magnetometer survey also, and the most important gravity anomalies were checked with the seismograph.

During the ten years of exploration (from 1933 to 1943) about 20,000 torsion balance stations, 12,000 gravity meter stations and 15,000 vertical magnetometer stations were made. Seismograms were recorded at 2,500 shot points.

A summary of the results of these geophysical investigations and of the geological interpretation of the geophysical data will be presented. A schematic tectonic map of southwest Hungary presenting a geological interpretation of the results of the combined geophysical methods is also enclosed. All the material presented here is compiled from about forty reports prepared by the author during the ten years of exploration in Hungary.

Due to the involved political conditions, some of the geophysical data obtained during the war are not now available and for this reason the enclosed gravity and magnetic maps are not complete. However, the schematic tectonic map (Plate 3) contains the geological interpretation of all the geophysical data obtained up to the end of 1943.

II. THE APPLICABILITY OF THE VARIOUS GEOPHYSICAL METHODS IN SOUTHWEST HUNGARY

The topography of southwest Hungary—excluding the mentioned Mesozoic and granite mountains—is mostly plain or moderately hilly. Apparently most of the territory is suitable for torsion balance surveying. However, there are areas of moderate extent even on the plains where the results of the torsion balance survey are greatly disturbed. This is due partly to the marshy soil (for instance, in the northwestern corner of the area and at the southwestern end of Lake Balaton) and partly to irregularly distributed gravel masses near the surface (north of Mihályi along the Danube).

On the other hand, with due care and technical skill, successful torsion balance surveys were made even in relatively hilly areas which gave valuable information concerning at least the essentials of the geological structures (as in the environs of Lispe[3] (N46°32′ E34°22′), Igal (N46°32′ E35°36′), Pincehely (N46°-

40′ E36°06′), etc. It is believed that this was possible because of the exceptionally uniform density of the topographic features, formed mainly of clay and sand.

The lithological section in southwest Hungary—as far as can be judged from the well logs, from geological investigations made at the margin of the basin, and from density determinations on core samples—follows the general rule that the density increases with depth. For this reason it may be supposed that high gravity values (positive gravity anomalies) correspond to structural highs and low gravity anomalies correspond to structural lows. Consequently, most of this area ought to be susceptible to exploration by the torsion balance. The entire area of southwest Hungary is favorable for gravity meter survey but communication difficulties handicapped the work at some places.

The lithologic section in southwest Hungary is not very favorable for seismic investigations. The intermediate surfaces of strongly stratified sedimentary rocks (clay, marl and sand) of great thickness would appear favorable, but they yield rather weak reflections. Furthermore the lenticular nature of the beds makes correlations of reflections extremely difficult, if not practically impossible. Because of the great number of reflecting surfaces only a small portion of the seismic energy reaches the basement.* In addition, the surface of the basement is probably, in most cases, badly eroded. This is shown, for instance, by core samples from the wells drilled at Mihályi (N47°31′ E34°45′) (crystalline schists), at Hahot (N46° 38′ E34°46′) (Triassic limestones), and at Kaposvár (N46°21′ E35°27′) (phyllite). In some cases where the basement is rather shallow, reflections from the basement cannot be distinguished from reflections from a hard marl bed. Interpretation of seismic reflections must be based primarily on dips. Correlation may be attempted at some places only to supplement the dip data.

In general, no direct success may be expected from the magnetometer survey when prospecting for oil. Due to the rather regular density distribution in southwest Hungary, an estimate of the basement depth can be made more reliably from the gravity data than from magnetic anomalies.

It appears that the basement rocks in most parts of this area (granite, various crystalline schists, Mesozoic limestones) have very little or no magnetic effect and for this reason their configuration cannot be determined by the magnetic method. The basic volcanic rocks occurring in the area (basalt, basalt tuffs, trachydolerite, pyroxene andesite) can be clearly detected by the magnetic method. They are of small areal extent.

Due probably to intrabasement masses of relatively high magnetic susceptibility, geological trends of the basement complex can be fairly successfully traced by the magnetic anomalies. The most useful practical application of the magnetic method in this region was the location of basalt plugs in those areas where loca-

* From a geophysical point of view, the complex of the dense rocks with high elastic modulus (limestone, crystalline schists, granite, etc.) under which no rocks with lesser density and elastic modulus (marl, sand, etc.) may be expected, is regarded as basement.

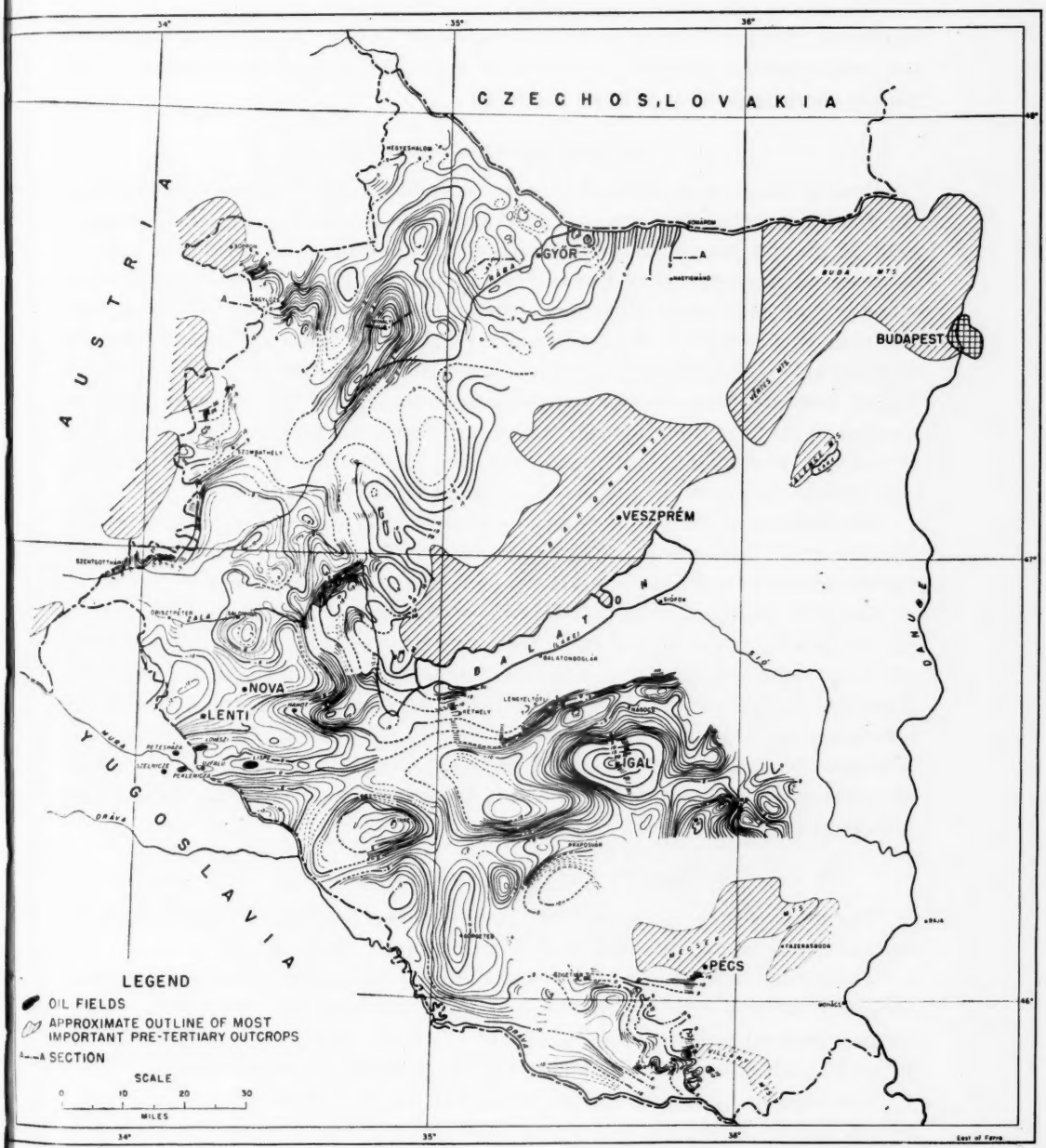


PLATE 1. Gravity map of Southwestern Hungary.

tions for wells were to be made. In this way drilling into volcanic plugs could be avoided.

The above discussion may explain that the gravity method was useful in southwest Hungary not only for reconnaissance but for detail work also. Both the torsion balance and the gravity meter were used, and gravity anomalies were mainly considered when locating test wells.

III. GEOLOGICAL INFORMATION

Prior to the granting of the European Gas and Electric Company's concession, the Hungarian Oil Syndicate (a subsidiary of the Anglo Iranian Oil Company) held an oil and gas concession in Hungary. This company drilled two wells in southwest Hungary, one at Budafapuszta (N46°31′ E34°22′) which penetrated 5,699 feet of Pannonian (Pliocene) sediments with some oil and gas shows, and one near Kurd (N46°27′ E35°59′) which reached the Miocene formation at 984 feet and also showed some oil traces. These wells were drilled on the basis of geological considerations without geophysical investigation. As was mentioned in another paper,[3] the Budafapuszta well was drilled in a search for the continuation of the east-west striking anticline of the long known small oil fields of Szelnicze and Peklenicza located in Jugoslavia, near the Hungarian border.

The Budafapuszta well showed first that the Tertiary strata have an exceptionally great thickness in southwest Hungary. Previously it was believed that the thickness of the Pliocene strata does not exceed a thousand feet.

Detailed geological work was done mostly in the mountainous area. However, the entire area was surveyed and a tectonic map was published by Pávai-Vajna[4] showing numerous folds crossing this Neogene basin mostly in an east-west direction. As this map was based on surface observations which are, for the above mentioned reasons, mostly unreliable, it is no wonder that results of the geophysical investigations and of the subsequent deep drilling gave a completely different picture of the geology of southwest Hungary than was shown on the map published by Pávai-Vajna.

IV. GRAVITY MAP OF SOUTHWEST HUNGARY

The gravity map of southwest Hungary shown on Plate 1 combines the results of the torsion balance survey and of the gravity meter survey.

The torsion balance and gravity meter surveys were first carried out as reconnaissance surveys with stations located along traverses five to ten miles apart. Station interval was in general one-third of a mile. Gravity anomalies were detailed by a net of stations with an interval of one-third of a mile or less.

The isogams calculated on the torsion balance observations are adjusted to a net of gravity meter stations which were tied through a pendulum station at Budapest to the Potsdam system. All the gravity values are Bouguer anomalies. Latitude corrections were made by the 1930 International Formula. The isogam interval is one milligal. The isogams calculated on the torsion balance data could

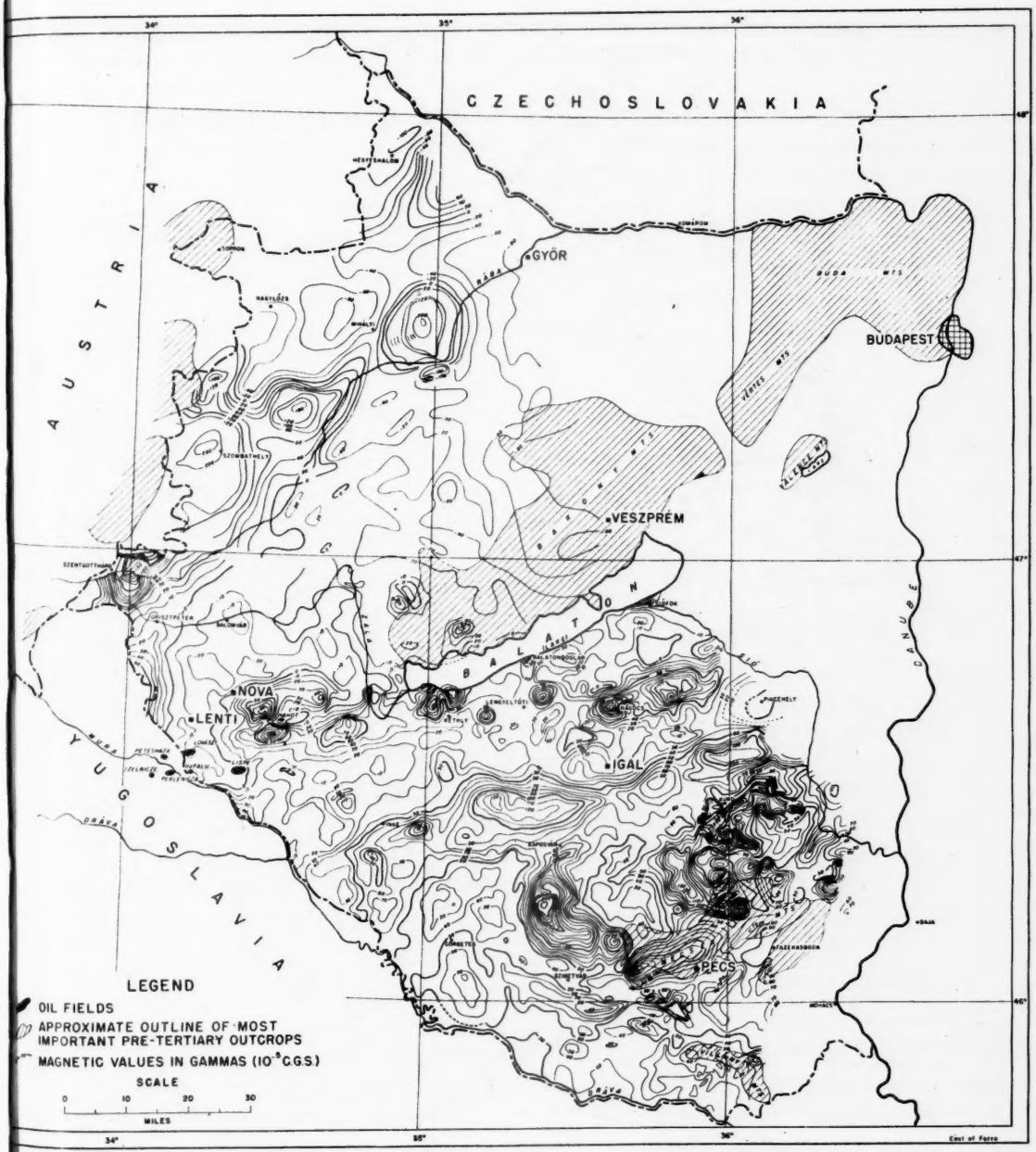


PLATE 2. Magnetic map of Southwestern Hungary.

PLATE 3. Schematic tectonic map of Southwestern Hungary, based on geophysical investigations.

be adjusted rather well to the net of gravity meter stations and to the relative pendulum stations which were later checked by the gravity meter. In most cases one to one-and-a-half Eötvös unit correction in the observed gradient values was sufficient for the adjustment. A correction as high as about three Eötvös units was not often needed.

The isogams show no apparent regional gravity effect and no regional correction of the gravity data was necessary in southwest Hungary. Isogam values of 30–35 milligals were observed at the western extremities of the area where the crystalline basement outcrops, while east of the Danube, at about the center of the Great Hungarian plains, basement depths of about 6,500 feet correspond to the same gravity values. This lack of a direct relation between depths to a density contrast and corresponding gravity anomalies is a common experience.

The gravity data east of Lake Balaton and Lake Velence are not now available.

V. MAGNETIC MAP OF SOUTHWEST HUNGARY

Most of the concession was covered by a vertical magnetometer survey. The station interval was, in general, two miles. Some magnetic anomalies and the most important gravity anomalies were covered by detailed magnetometer surveys with station intervals one-third of a mile or less.

The results of the magnetometer survey are shown on Plate 2. The northern part of the survey was made with an old Schmidt magnetometer without temperature compensation and for this reason, the anomalies in this part of the area are less reliable.

The rest of the magnetic anomalies shown on this map were observed with the same instrument but with a new temperature compensated magnet system. The accuracy of this survey is still not very high, being about plus or minus 4.5 gamma. The contour interval of the vertical intensity maps is 10 gammas.

The magnetic anomaly data obtained in the area east of Lake Balaton and Lake Velence are not now available. Horizontal intensity measurements were made in the Inke and Hahot areas, but these results are not available either.

VI. GEOLOGICAL INTERPRETATION OF THE GEOPHYSICAL SURVEYS

The results of the various geophysical surveys were studied in detail, and the results of these studies were compiled in a schematic tectonic map of southwest Hungary shown on Plate 3. The geological features shown on this tectonic map will be discussed below in relation to the corresponding gravity and magnetic anomalies presented on Plates 1 and 2. Detailed maps of the most important structures are also presented.

A study of the gravity and magnetic anomalies proves that, geologically, southwest Hungary (also called Transdanubia) is not a uniform area but is divided into several parts of structurally different character.

1. *Structure of the Little Hungarian Plains*

Only the southern part of the Little Hungarian Plains is in present Hungary. It lies south of the Danube between the towns Komarom (N47°45′ E35°48′), Papa (N47°20′ E35°10′), Szombathely (N47°14′ E34°17′) and Sopron (N47°40′ E34°15′). (See Plate 3.)

The geological structures indicated by the gravity anomalies in this area are listed below.

a. *Györ Basin*

The large gravity minimum existing in the environs of Györ (Plate 1, N47°40′ E35°20′) can be explained by a great basement low filled probably with Tertiary and Quaternary deposits. The deepest part of this basin, corresponding to the closure of the isogams with lowest values, is located in the vicinity of Györ. From the available data, the basement rocks are probably at least 12,000 feet deep and possibly much deeper.

The Györ basin is limited to the east by faults striking in a northeast-southwest direction in the vicinity of Komárom and Ács (N47°42′ E35°41′). These faults are downthrown toward the northwest. Based on the relatively small number of torsion balance stations, only three major faults could be located with sufficient accuracy (Plate 3). The Mesozoic limestone basement rocks outcropping in the vicinity of Tata (N47°38′ E35°59′) drop apparently stepwise toward the west in the direction of the Györ basin. During the gradual sinking of the basement, here and there a block remained in a relatively high position as in the vicinity of Tata, Mocsa, Kocs, Dad, and Veszprémvarsány (N47°25′ E35°31′) as indicated by corresponding gravity maxima. To the north the Györ basin extends beyond the Danube and probably only about half of it is within the Hungarian border. To the southeast the Györ basin becomes narrower and terminates at about Celldömölk (N47°15′ E34°50′). An embayment toward the Bakony Mountains joins the southwest end of the Györ basin. This is formed by the "down dropping" of a block of the subsurface continuation of the Bakony Mesozoic mountain system.

East of Mihályi the magnetic survey shows a large, round magnetic maximum with a relative intensity of about 300 gammas (Plate 2). No corresponding gravity maximum was found—only a much smaller gravity maximum is indicated southwest of the center of this magnetic maximum, but obviously this cannot be related to the large magnetic maximum. It may be safely supposed that this magnetic maximum is due to a change of magnetic susceptibility of the basement rocks without corresponding density changes, or geological structure.

b. *The Buried Hill Structure of Mihályi*

At the western side of the Györ basin, the gravity anomalies indicate a thirty-five mile long, strongly faulted buried hill with three secondary highs (Plate 1). This is called the Mihályi structure. All three highs on this structure were drilled.

According to the data from the first well located on the central high of the

structure at Mihályi, the top of the buried crystalline hill (quartzite and phyllite) is at 5,256 feet. The crystalline basement rocks are directly underlying Lower Pannonian (Pliocene) strata. The second well drilled four miles north-northeast of the first well reached the Paleozoic basement at 8,095 feet and the third well, located halfway between the first two, at 6,227 feet. This shows that the top of the structure is rather flat, as was expected from the gravity anomalies. The side of the structure has a dip of about 10° in this direction, which is in accordance with the seismograph survey. Neither of these wells penetrated beds older than Pliocene above the crystalline basement. The first well produced 15 million cubic feet of CO_2 with 5 per cent distillate from Lower Pannonian sands between 4,900–5,100 feet.

The fourth well, drilled about 17 miles north-northeast of Mihályi on the northern secondary high of the structure, reached the crystalline basement at 8,698 feet. This well encountered 285 feet of Miocene formation lying directly on the crystalline basement and was abandoned as a dry hole.

The fifth well was drilled on the southern secondary high of the structure at about 9 miles southwest of the first well. This well reached the basement at 4,790 feet and yielded a great quantity of CO_2 with 5 per cent hydrocarbons. It has essentially the same geological log as the first well.

The detailed torsion balance map of the Mihályi structure (part of which is shown on Figure 4) showed some very small but sharp gravity maxima. As some basalt tuffs were found in a few cores taken from the first well at Mihályi, it was supposed that these small gravity maxima are due to volcanic plugs at relatively shallow depths. Similar basalt tuffs were found at the surface in the vicinity of Gérce (south of the Mihályi structure—see Plate 3), and it is known that some volcanic activity occurred during the Pliocene.

A detailed magnetometer survey was made over the northern half of the Mihályi structure to investigate this hypothesis. (See Plate 5.) This survey showed small magnetic maxima of 30 to 80 gammas intensity, coinciding with the small gravity maxima. Computation showed that the tops of these supposed volcanic plugs are at depths between 1,500 and 3,000 feet. Similar magnetic indications were found near the fifth well on the southern high of the Mihályi structure. These volcanic plugs may explain the presence of the CO_2 gas in the Mihályi wells.

The reconnaisance magnetic map (Plate 2) shows a large magnetic maximum southwest of the Mihályi structure which is probably due to intrabasement magnetic masses. However, this magnetic maximum has a "nose" in the north-northeast direction coinciding with the southwestern part of the Mihályi structure. This may indicate that the southwest part of the structure has a crystalline core (possibly granite) with higher magnetic susceptibility than the crystalline schists forming most of this structure. It should be mentioned, however, that the well drilled here reached crystalline schists also and thus the granite should form, if present, the core of the crystalline schist structure.

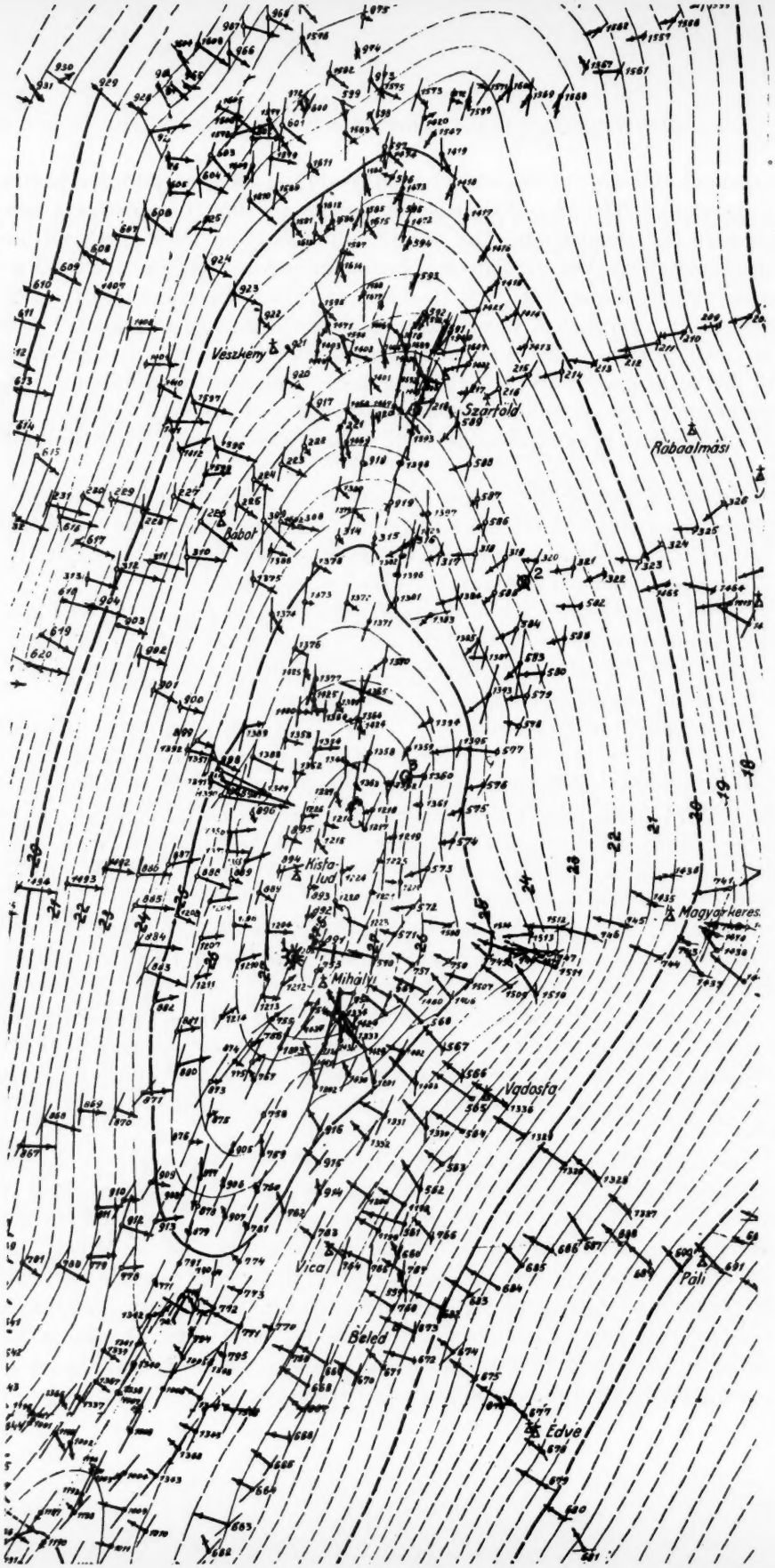


PLATE 4. Detailed torsion map of the Mihályi structure.

The reflection seismograph survey on the Mihályi structure indicated a Pliocene structure formed probably by differential compaction above the buried crystalline hill. Due to the lenticular structure of the Tertiary formations, as mentioned above, no correlation of the reflections was possible. A contour map of a Pliocene phantom horizon (Figure 6) presents a picture of part of the Pliocene structure at Mihályi. There the axis of the seismic high agrees very well with the gravity high. North of Mihályi the axis of this seismic structure is displaced toward the west as compared to the gravity axis. This discrepancy is probably due to the uncertainty in the weathering corrections and possibly to some asymmetry in the Pliocene structure above the buried hill.

The reflections indicate increasing dip with depth. No reflections could be distinguished by intensity or character as coming from the surface of the basement. This is due to the numerous reflecting surfaces in the Pliocene formations, as was explained above. No reflections were expected to come from within the basement and the surface of the basement was assumed to lie just below the deepest reflections.

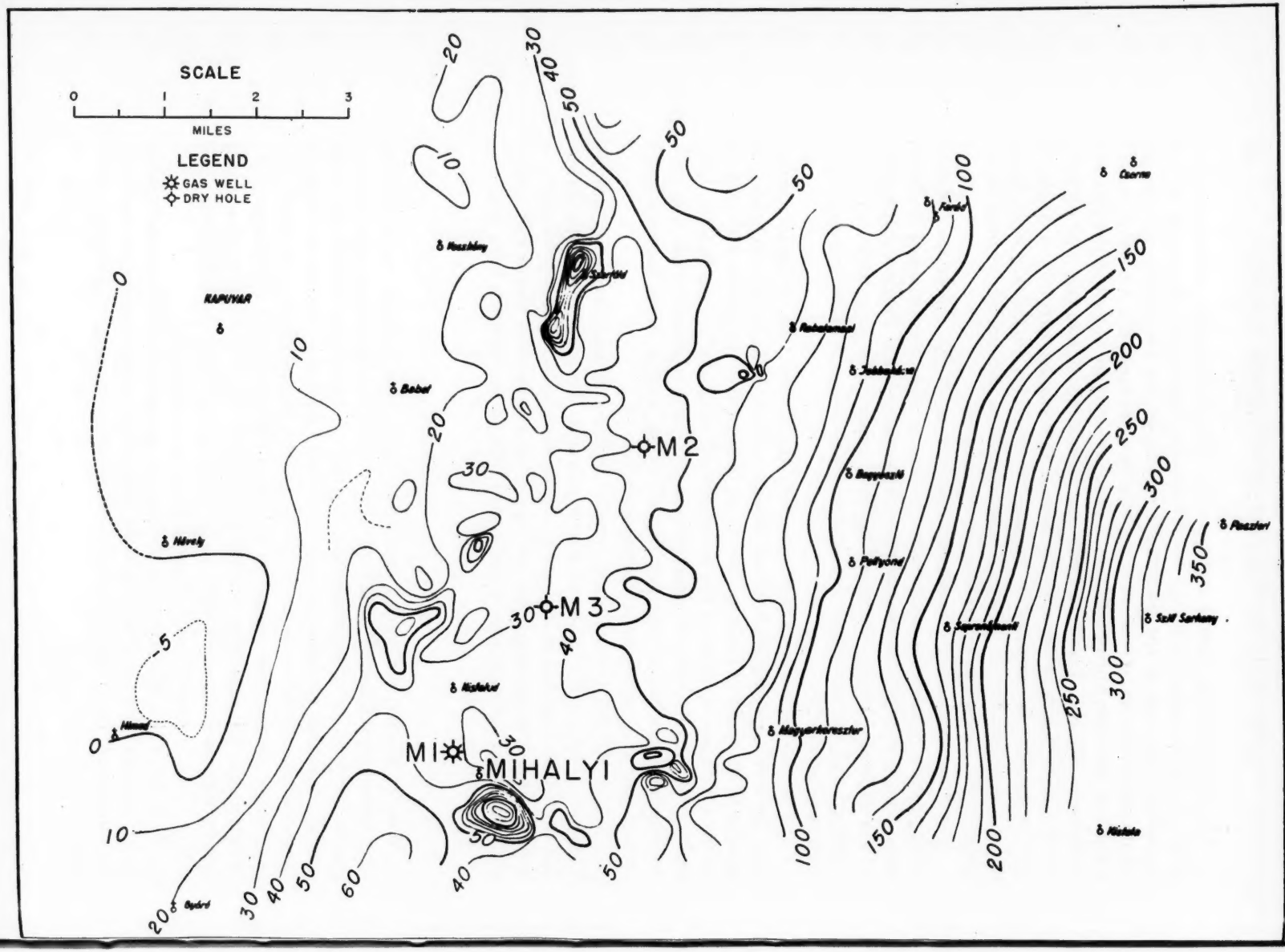
The torsion balance data indicate several faults dissecting the Mihályi structure, the most important of which are shown on Plate 3. Some of these faults are parallel to the strike of the structure; some of them are cross faults. Probably all are normal faults. As most of the known basalt volcanoes around Balaton Lake are located on fault lines, and especially at the points where the strike and cross faults intersect, it seems probable that a similar relation exists between faults and volcanic plugs at the Mihályi structure also.

East of Mihályi the gravity anomalies indicate a small secondary gravity maximum (Plate 1). No similar magnetic indication was found here and therefore this cannot be regarded as indication of volcanic masses. This may be due to a sedimentary structure overlying, perhaps, a small basement horst. This indication was found during a later detail survey and no test well has been drilled as yet on this indication.

c. *The Nagylózs Structure*

West of Mihályi the gravity anomalies indicate the northern end of another large buried crystalline hill structure. The first data showed three small distinct gravity maxima, but additional data proved that these were details of a large gravity maximum extending to the south from Nagylózs. The gravity high at Hegyeshalom may be connected with this gravity maximum. It is obviously due to a buried hill structure similar to the one at Mihályi. After the failure of the Mihályi wells this structure was not investigated much further. A pronounced gravity minimum is located between the Mihályi and Nagylózs structures, indicating a long basement trough between these two structures.

West of the Nagylózs structure, the gravity anomalies indicate another graben in the basement and then, further to the west, rising gravity values correspond to the emerging of the crystalline schists and to their outcrop in the vicinity of Sopron.


SCALE
0 1 2 3
MILES
LEGEND
GAS WELL
DRY HOLE
KAPUVAR
M1
MIHALYI
M2
M3

A hypothetical geological section (marked A–A on Plate 1) was constructed through the Nagylózs and Mihályi structures and through the Győr basin (see Plate 7). This section is based on the gravity data and well logs and shows the fault system at the eastern margin of the Little Hungarian Plains, as well as the two buried hills at Mihályi and at Nagylózs. Relatively high basement blocks are shown corresponding to the small intensity gravity highs within the Győr basin. As some flexures may be expected above these basement highs, this particular area is prospective for oil production.

Without changing laterally the density values, the writer was unable to compute a satisfactory section which would correspond to the geological data furnished by well logs at Mihályi and by outcrops in the vicinity of Sopron, and which at the same time would be in agreement with the gravity data. For this reason, the given geological section should be considered as a qualitative rather than as a quantitative interpretation of the gravity data.

2. *Structure of the Area between Szombathely-Sümeg-Nagykanizsa and the Jugoslavian and Austrian Borders*

a. *The Lenti-Őriszentpéter Basin*

An examination of the gravity map (Plate 1) shows that this area, which lies between N46°30′ and 47°15′ and between E34° and 35° is geologically very much disturbed. The crystalline basement, which outcrops along the Austrian border, drops along the northeast-southwest and north-south striking faults into great depths and forms a large basin. This basin is indicated by the gravity minimum approximately outlined by isogam −5, with its deepest part probably in the vicinity of Lenti (N46°37′ E34°14′). To the east this basin is bordered by submerged blocks of the Bakony Mountain system, dissected by numerous northeast-southwest and northwest-southeast striking faults. It was attempted to give a schematic picture of these extremely disturbed, submerged blocks and of the most important faults indicated by the gravity survey in this particular area on Plate 3. Most of these blocks are probably at a relatively shallow depth and for this reason they have no practical value in prospecting for oil.

The magnetic survey showed a general magnetic low (see Plate 2). Pronounced magnetic anomalies were found within this basin but only in the vicinity of Hahot where four magnetic maxima were indicated. These anomalies will be discussed later. West of Lenti along the Jugoslavian border, part of a large magnetic maximum is indicated, but its major part and its apex are beyond the Hungarian border. This magnetic maximum is probably due to intrabasement masses. However, a gravity high corresponds to this magnetic high beyond the border. It is possible that actually an igneous basement horst is present here, which consists of rocks with high magnetic susceptibility. Similarly, the gravity and magnetic maxima in the vicinity of Szentgotthárd (N46°57′ E33°55′) probably indicate the subsurface continuation of the basement outcrops north of Szentgotthárd.

Several gravity maxima interrupt the large gravity minimum corresponding

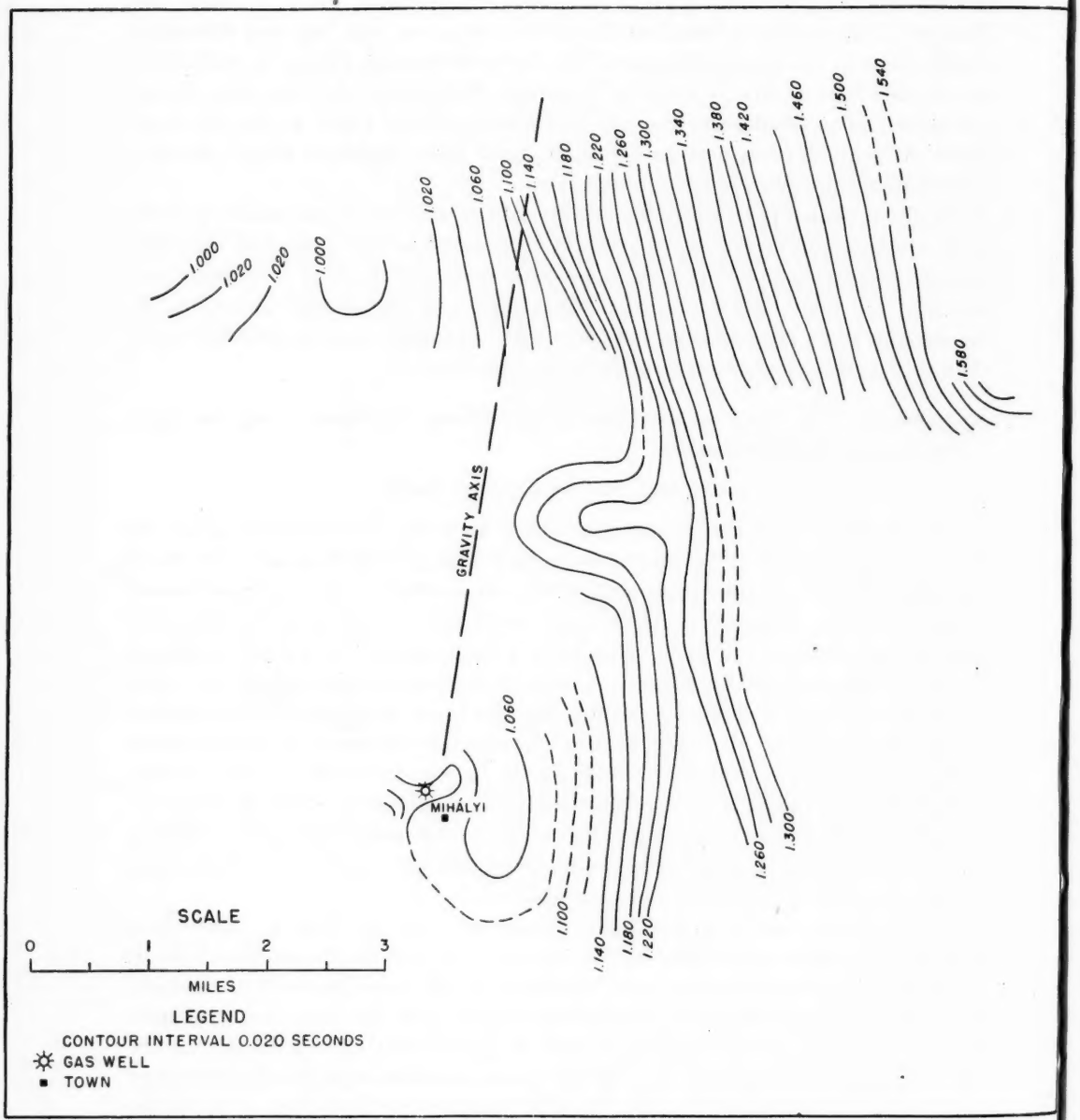


PLATE 6. Seismic map of the Mihályi structure. Phantom horizon.

to the Lenti-Öriszéntpeter basin. These correspond partly to the mentioned submerged blocks of the Bakony mountains and partly to sedimentary structures.

b. *The Salomvár Structure* (N46°52′ E34°20′)

A more or less round gravity maximum indicates a Mesozoic horst, the westernmost block of the submerged part of the Bakony mountains. A well located on this prospect reached Mesozoic limestones at a depth of 7,244 feet. Besides Pliocene strata the well encountered 331 feet of Miocene limestones directly overlying the Mesozoic buried hill. An oil show was recorded in the Miocene. Encouraged by the oil show a second well was drilled on this structure but without success.

It is interesting to note that the seismograph survey on this structure failed to indicate a closed structure. The reflections showed only southwest dipping strata without any reversal over the entire gravity maximum at Salomvár. This is one of the two instances (the other being the Görgeteg prospect—see below) where there are essential differences between the gravity anomalies and the seismic indications in southwest Hungary.

c. *The Nádasd Structure*

North of the Salomvár, a small gravity maximum was found by the torsion balance. Though the anomaly is too small to show a closure in the gravity meter isogams, the gradients show a complete reversal. This gravity anomaly was interpreted as an indication of a small anticline. The seismograph survey also showed a small east-west striking structure corresponding to this gravity maximum. The test drilled on this prospect turned out, however, to be a dry hole.

d. *The Nagytilaj Structure*

A northwest plunging Mesozoic block was postulated at Nagytilaj (see N. Tilaj N46°58′ E34°37′—Plate 3) based on a northwest-southeast gravity nose indicated by the torsion balance survey. A small closure of about two milligals is shown on this nose. This anomaly is cut off to the southeast by a northeast-southwest striking fault, with downthrown side to the northwest. This fault is the margin of another Mesozoic block in a relatively higher position. The seismograph survey showed reversed dips corresponding to the gravity nose at Nagytilaj.

This prospect has not yet been tested.

e. *The Budafapuszta (Lispe) Anticline*

As was discussed in another paper,[3] two small oil fields were discovered a long time ago in Jugoslavia right across the national frontier. Both of these oil fields are located on an east-west striking anticline. It was supposed that this anticline, which in Jugoslavia is easily discerned on the surface, extends across the border into Hungary and this continuation was searched for. However, the Lower Pannonian (Lower Pliocene) strata, which outcrop at Szelnicze in Jugoslavia, are not

THE LITTLE HUNGARIAN PLAINS

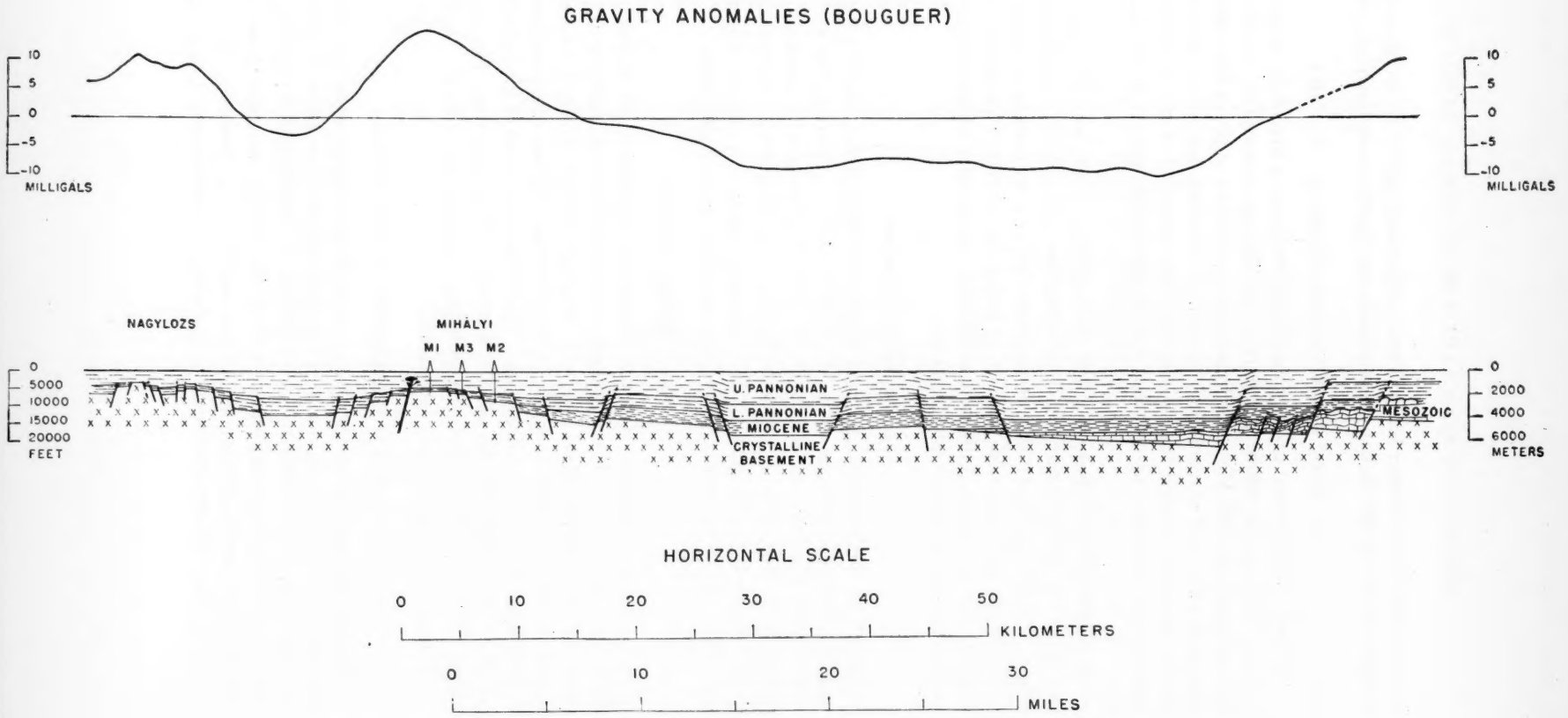


PLATE 7. Gravity curve and hypothetical geological section through the Little Hungarian Plains. Section A–A.

present on the surface in Hungary, and the Upper Pannonian is without reliable stratification. For this reason the continuation of this anticline in Hungary could not be definitely determined by surface geological methods. This explains why the exploratory well drilled by the Hungarian Oil Syndicate (affiliate of A.I.O.C.) in 1921 at Budafapuszta (N46°31′ E34°22′) without previous geophysical investigation, was a failure. It missed the water-oil contact of the Lispe oil field, discovered here later, by 1,600 feet.

The torsion balance survey made in this area indicated a twenty-mile long east-west striking gravity maximum. Its width from syncline to syncline is about eight miles at the eastern end and about fifteen miles at the west end along the border. Three secondary highs are shown on this great gravity maximum. The first one is at Lispe (N46°32′ E34°22′), the second at Ujfalu (N46°31′ E34°14′), and the third at Lovászi (N46°33′ E34°14′). This large gravity maximum was interpreted as an extension of the Szelnicze anticline, and the secondary gravity maxima were regarded as indications of three domes on the crest of the main anticline.

The two parallel domes at Ujfalu and Lovászi caused some speculation, as a double crest in the western part of the anticline seemed improbable. When the torsion balance data were still incomplete, it seemed possible that the secondary gravity maximum at Lovászi was due to an inverse fault and an alternative interpretation was offered on this feature. Later when the gravity data were more complete, the fault interpretation was discarded and the "parallel dome" assumption was accepted. All three domes were drilled and all three were oil bearing. Structure contour maps based on the well data proved that the Lovászi oil field, like the other two, i.e. Lispe and Ujfalu, is also a dome on the main Budafapuszta anticline.

Detailed geophysical maps and sections of the Budafapuszta, or Lispe oil field were given in the other paper mentioned above. Figure 8 shows actual subsurface structure contour lines of the Lovászi oil field and the gradients observed by the torsion balance in the same area. There is a very good agreement between the structure and the gravity anomalies.

It is interesting that, although the structure of the Budafapuszta anticline and of the three domes were correctly interpreted, the comparative rating of these three domes as potential oil fields was erroneous. Due to the proximity of the Szelnicze and Peklenicza oil fields the dome at Ujfalu was regarded as most promising. The Lispe dome was rated second and the Lovászi dome, because of its offset position, as third. Actually the Lovászi oil field proved to be the most productive with an estimated recoverable reserve of 35 million barrels, the Lispe oil field with 30 million barrels of reserve rates as second, whereas Ujfalu was abandoned as non-commercial after two years of production.

There is no geophysical indication that the Budafapuszta anticline has a limestone or crystalline core. It is regarded as a fold formed during the Tertiary. Tertiary folding did not affect the Mesozoic mountains in southwest Hungary and for

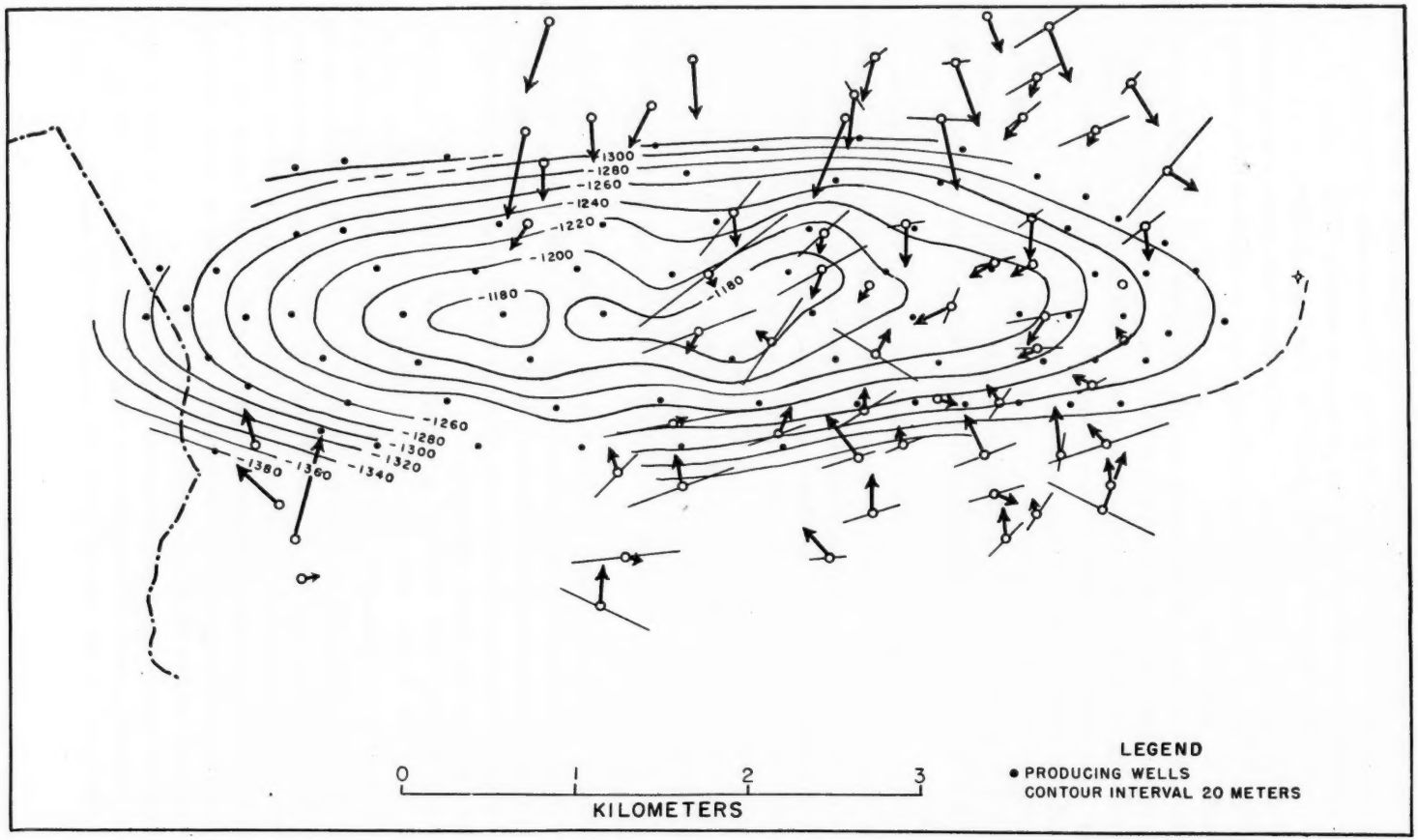


PLATE 8. Actual subsurface contour map and torsion balance data of the Lovászi oil field.

this reason it may be supposed that the Lispe anticline has no folded Mesozoic or older core. However, as it will be shown later on the Hahot structure, a deep seated Mesozoic horst may be the core of this Tertiary fold.

As was mentioned above, the Budafapuszta anticline is located in a magnetic low area. No small magnetic maxima, similar to those at Mihályi and at Hahot (N46°38′ E34°36′), were found over the Budafapuszta structure. This indicates that no volcanic intrusions are present here. It is interesting to note that the gases of the three oil fields on the Budafapuszta anticline contain no appreciable amount of carbon dioxide, while the gases found at Mihályi and in those areas where volcanic intrusions were indicated by the magnetic survey contain a large amount of carbon dioxide.

The axis of the gravity maximum indicating the Budafapuszta anticline runs in an east-west direction. However, its eastern end swings to the northeast and here the gravity axis is parallel to Lake Balaton and to the general strike of the Bakony Mountains. There is no eastern closure of the main gravity maximum, except the closures of the domes on the crest of the structure, and the gravity maximum changes here to a southwest plunging gravity nose. This gravity nose was interpreted as a subsurface Mesozoic horst, a submerged part of the Bakony system. A well drilled on this gravity nose near Ujudvar (see Plate 3) reached the top of the Miocene at 7,277 feet and was abandoned as a dry hole without reaching the assumed Mesozoic horst. Such a submerged horst may have been a factor in the initial development of the Budafapuszta anticline.

Only the eastern end of the syncline indicated south of the Budafapuszta structure is within Hungary. It probably broadens to the west.

North of Budafapuszta the eastern part of the syncline is well developed. It plunges to the west and runs into the large Lenti-Öriszentpéter basin.

f. *The Hahot Structure*

Northeast of the Lispe oil field at Hahot, a west plunging gravity nose indicates a subsurface structure. The eastern end of this gravity maximum nose turns sharply to the northeast. At first this gravity anomaly was regarded as the gravity effect of two joining structures: a northeast-southwest striking subsurface horst of the Bakony Mountain and an east-west striking anticline, a fold similar to the Budafapuszta anticline attached to the above mentioned horst structure. Subsequent drilling proved that this interpretation was not quite correct inasmuch as not only the NE-SW striking part, but also the east-west striking part, of the gravity maximum is due to a horst; however, there is a Tertiary structure above the latter. It was rather unexpected to find an east-west striking Triassic horst when the general strike in the Bakony mountains is northeast-southwest.

The seismograph survey showed also a west plunging structure but the axis of the seismic structure is somewhat to the south as compared to the gravity axis (see Figure 9). The gravity anomalies indicate several cross faults. Presence of cross-faulting is inferred also from the well data.

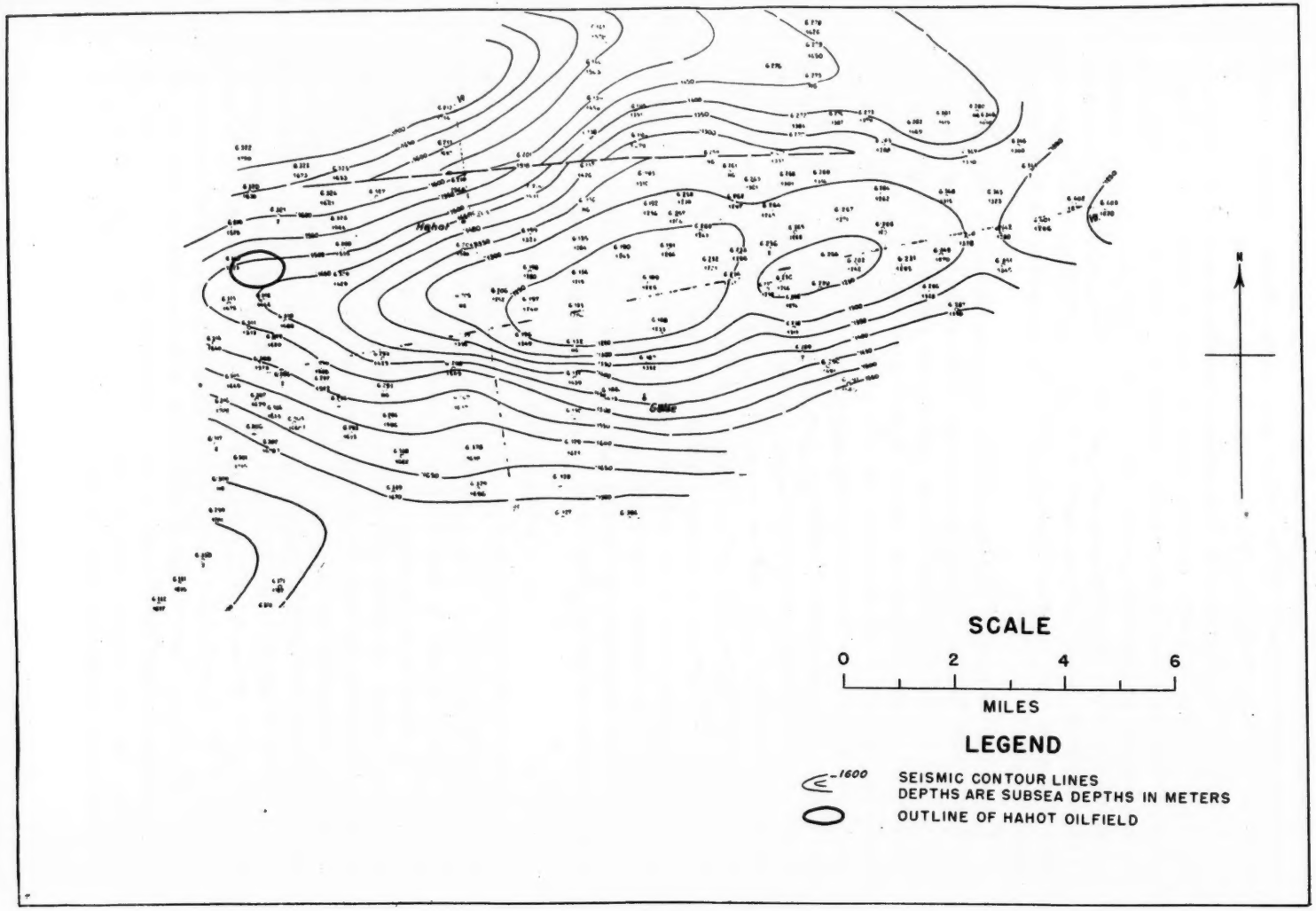


PLATE 9. Seismic map of the Hahot structure.

The first well, located east of Hahot, encountered Triassic limestone at 2,495 feet directly underlying the Pannonian (Pliocene). The second well, somewhat south of Hahot, found the same formation at a depth of 2,959 feet. A few feet of Miocene (Lithothamnium) limestone is on top of the Triassic limestone. The third well, drilled four miles west of Hahot, hit the Triassic limestone at 4,690 feet with fifteen feet of Miocene resting directly on Triassic limestone. This well produced oil from the porous Miocene limestone and from fissures and crevices of the karst type Triassic limestones. Six additional productive wells were drilled around this well within a circle of 2,000 feet diameter. Other wells drilled in this area were dry holes. Only one more oil producer has been drilled so far on the Hahot structure about two miles east of the Hahot oil field.

The oil is produced most probably by water drive. The Triassic limestones (even in the Bakony Mountains) contain a large amount of karst water. But the oil also contains gas with a considerable percentage of carbon dioxide.

About three miles west of the oil producing area a gas field was discovered on the Hahot structure. It is called the Ederics gas field. Nine wells drilled in an area of about 1,200 acres penetrated gas-bearing Pliocene sands between 4,600 and 4,900 feet. Production capacity of these wells is about 27 million cubic feet of gas daily. The gas is a wet gas, containing about one gallon of gasoline to 1,000 cubic feet of gas. No appreciable amount of carbon dioxide is present in it.

The gas field extends from the crest of the structure over the north flank. Its northern borders are not yet established, and it is hoped that the structurally lower parts of the gas-bearing sands will produce oil.

The wells drilled on the Hahot structure (including about 20 dry holes) showed that this is a buried hill structure with a Tertiary structure above it. The oil field is on a topographic high on the Triassic horst which is bordered on the east by a cross fault with downthrown side to the west. The oil is probably Pliocene oil which migrated into the Miocene and Triassic limestones from the Lower Pannonian (Lower Pliocene) strata leaning with an angular unconformity against the sides of the buried Mesozoic horst.

The magnetic survey showed four magnetic maxima around the Hahot oil field. These are evidently due to volcanic masses which did not rise above the Mesozoic surface or were eroded to the same level. This conclusion is based on the gravity data, as no gravity maxima corresponding to these magnetic maxima were observed. The presence of carbon dioxide in the gases of the Hahot oil field may be explained by these igneous masses. The carbon dioxide may have migrated through faults and through the fractured cavernous Triassic limestones to the oil field, but it was apparently sealed off by thick, compact Pliocene marls from the Ederics gas field. One of the wells drilled in the Ederics gas field and located within the magnetic maximum northwest of the Hahot field reached hornblende-diorite-porphyry.

3. *Structure of the Area Between Balaton Lake and the Mecsek Mountains*

Southeast of Lake Balaton the gravity anomalies indicate the southeast dip-

PLATE 9. Seismic map of the Hahot structure.

ping of the crystalline schist basement, which is at a depth of about 200 feet at the southeast shore of Lake Balaton. It drops down to the southeast along a major fault or fault system, forming a deep trough nearly parallel to Lake Balaton. Four major buried hills were indicated here by the gravity anomalies. The available gravity data show only two of these maxima, one at Inke, southeast of Budafapuszta, and the other at Igal (N46°32′ E35°36′). The remaining two major buried hills at Pincehely (N46°40′ E36°06′) and Nemetker (N46°42′ E36°26′) are outlined on Plate 3. The greatest depth of the basement in this area is probably between Inke and Igal, corresponding to the closure of isogam −15. South of this basement depression a north-south striking gravity maximum was observed at Görgeteg which does not fit into the general northeast-southwest strike.

Gravity maxima of lesser extent were found at Kaposvár (N46°21′ E35°27′), Kurd (N46°27′ E35°59′, and Murga (N46°28′ E36°09′).

Several large northeast-southwest striking magnetic maxima were found in this area, which are probably due to intrabasement masses, as no corresponding gravity indications were observed. Small magnetic maxima are interpreted as volcanic intrusions of various sizes as marked on Plate 3.

The magnetic anomalies between the Mecsek Mountains and the Kaposvár and Kurd structures show a very disturbed pattern with a pronounced north-northwest south-southeast strike which is nearly normal to the regional strike of the area. The limited gravity survey made here shows also rather disturbed subsurface conditions. All these features will be discussed individually below.

a. *Faults Parallel to Lake Balaton*

A major fault system is indicated by the gravity anomalies running through the localities Marcali, Öreglak, Karád and Tab (Plate 3). This fault is a normal fault with downthrown side to the south and southeast, and its throw must be at least 3,000 feet at Marcali. The fault becomes shallower toward the northeast and its throw decreases in that direction.

The reflection seismograph survey indicated the presence of a fault at about Marcali, but the direction and amount of its throw could not be determined from the reflections.

Near the northeast extremity of this fault two small structures were indicated by the gravity anomalies on the upthrown side of the fault. (See Plate 3. The gravity data are not available.) Gravity indications of a fault similar to the above mentioned one were found near the northeast end of Lake Balaton. At Polgárdi (N47°03′ E35°59′)—as computed from the gravity anomalies—this fault should be almost at the surface and its throw about 1,500 feet.

b. *Volcanic Intrusions South of Lake Balaton*

Based on the magnetic survey, several subsurface basalt intrusions should be supposed in the area south of Lake Balaton. Indications of such intrusions were found north and northwest of Kéthely (N46°38′ E35°04′), between Kéthely and

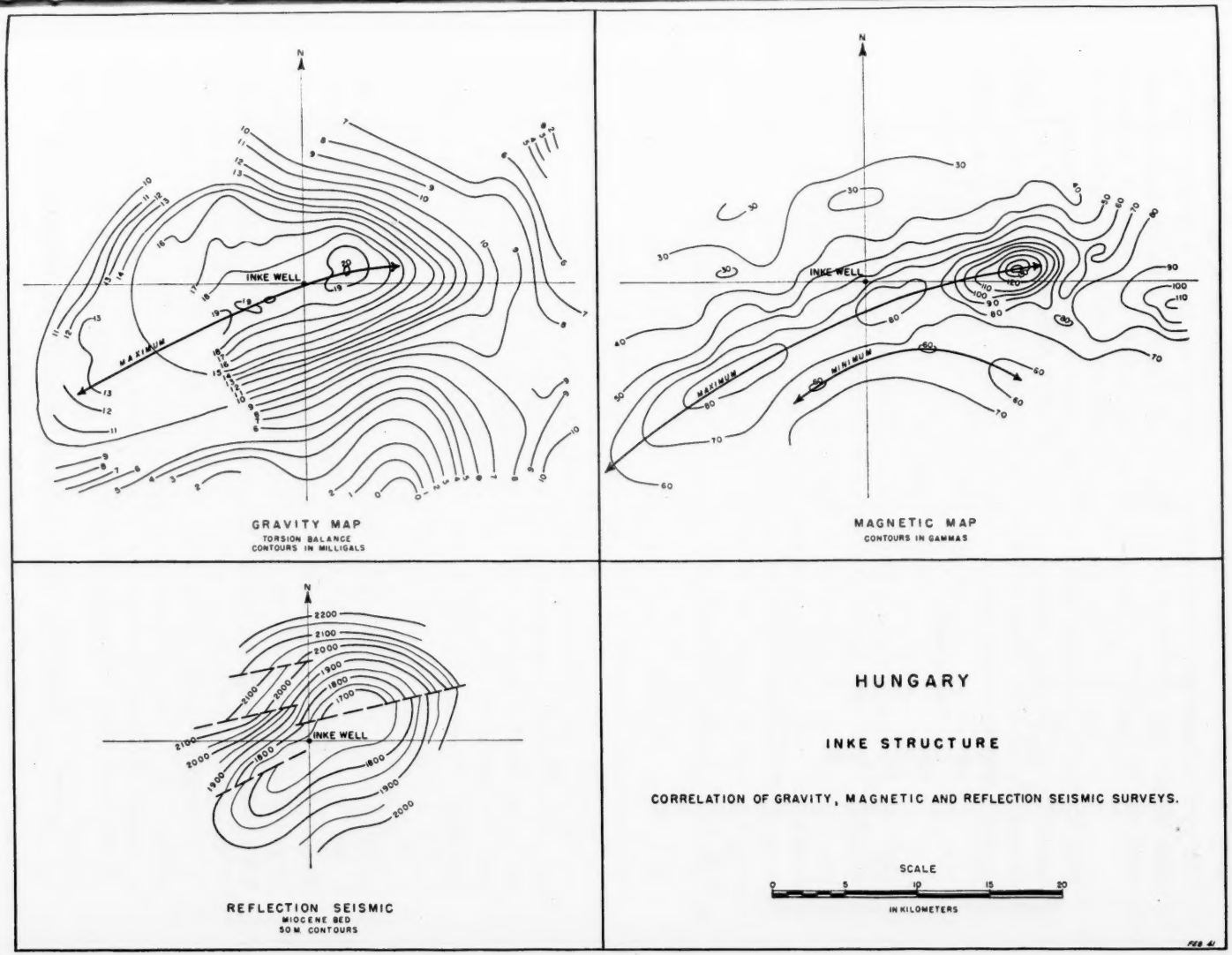

N
INKE WELL
MAXIMUM
GRAVITY MAP
TORSION BALANCE
CONTOURS IN MILLIGALS
N
INKE WELL
MAXIMUM
MINIMUM
MAGNETIC MAP
CONTOURS IN GAMMAS
N
INKE WELL
REFLECTION SEISMIC
MIOCENE BED
50 M. CONTOURS
HUNGARY
INKE STRUCTURE
CORRELATION OF GRAVITY, MAGNETIC AND REFLECTION SEISMIC SURVEYS.
SCALE
0 5 10 15 20
IN KILOMETERS

PLATE 10

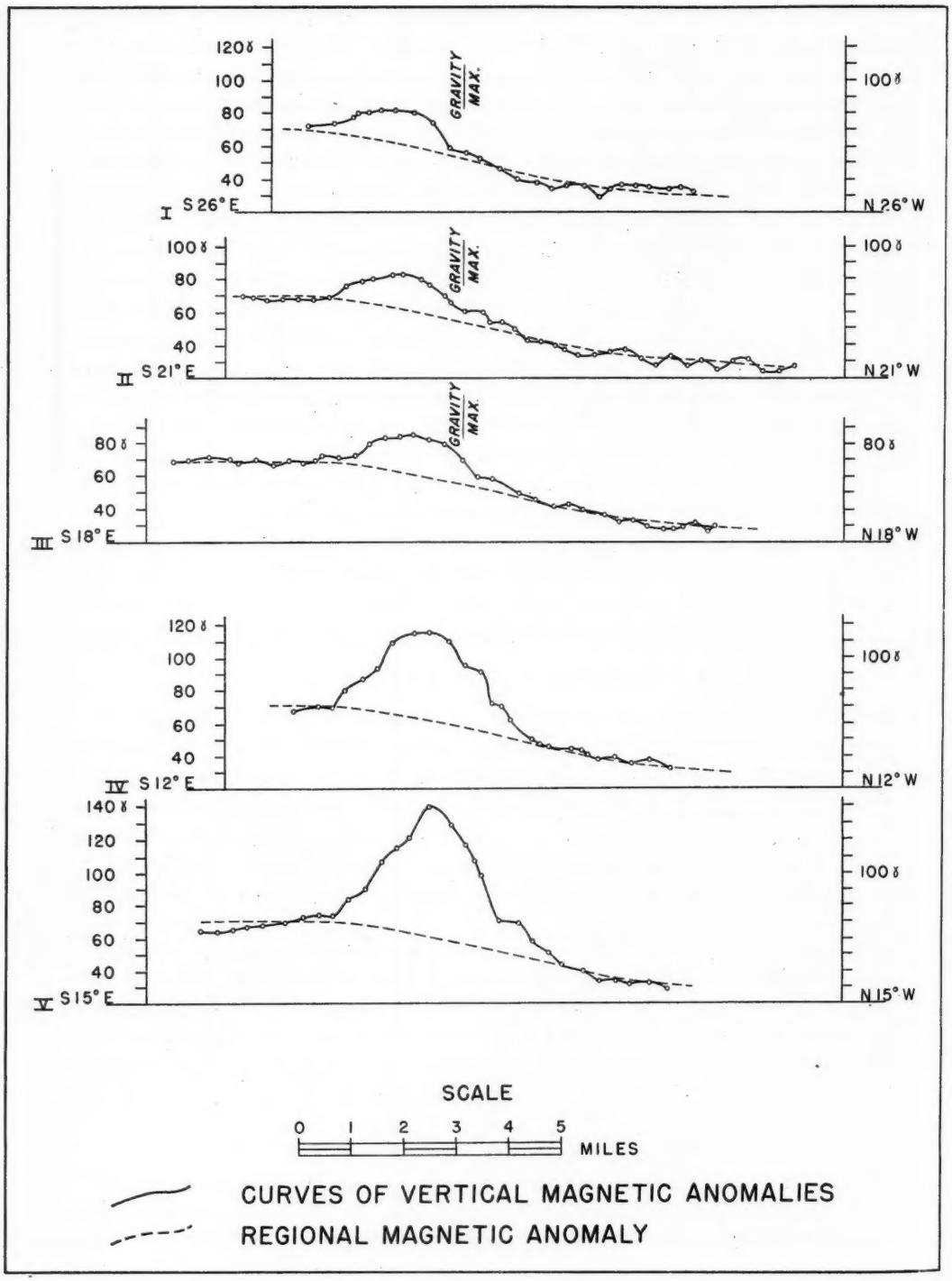


PLATE 11. Magnetic profiles across the Inke structure.

Lengyeltóti (N46°40′ E35°19′), and northeast of Lengyeltóti (Plate 2). Two similar indications were found in the vicinity of Balatonboglár (N46°47′ E35°20′) and two in the vicinity of Siófok (N46°54′ E35°44′). These intrusions consist most probably of basalt and gabbro and are probably at a shallow depth, at some places immediately below the surface.

Magnetic maxima of somewhat larger extent than the above mentioned were found at Nágocs (N46°40′ E35°38′) and east-northeast of Nágocs. The intrusions corresponding to these magnetic indications are probably at relatively greater depth and are of greater extent. It may be assumed that they consist also of basalt or of gabbro.

c. *The Inke Structure*

The triangle-shaped gravity maximum, with numerous closures, at Inke (N46°23′ E34°51′) is most probably the gravity effect of a buried hill structure (Plate 1 and 10). The torsion balance indicates several faults on the north and south sides of the structure corresponding to the sides of the triangle. The seismograph data show a Tertiary structure above this supposed buried hill. Dips of two to five degrees were observed. The axis of the seismic structure (see Figure 10) coincides with the gravity axis at the northeastern part of the structure, but they gradually deviate to the southwest, the seismic axis being further to the south than the gravity axis. This discrepancy is probably due to the fact that the location of the gravity axis is more influenced by the faults at the sides of the structure than by the relatively flat Tertiary structure above the buried hill.

Six wells were drilled on this structure. They confirmed the presence of a flat-topped Pliocene-Miocene structure with relatively steep sides. The closure in the Miocene is over 2,000 feet. No rocks older than Miocene were penetrated by the wells. Well I-1 reached the top of the Miocene at 4,744 feet and was drilled to a total depth of 7,023 feet, still in Miocene. Well I-6 was abandoned in Pliocene at 7,853 feet and was the deepest test on this structure. The first well produced about three million cubic feet of gas daily, containing over 30 percent carbon dioxide and a considerable amount of distillate. The other five tests drilled on this prospect were unsuccessful, though some of them showed oil and gas.

Here again the detailed magnetic survey (Plate 10[5]) indicates a volcanic intrusion, probably a large dike, striking parallel to the gravity axis but about two miles south of it. The magnetic anomalies indicate that the greatest igneous mass is at the eastern end of the structure. The profiles constructed across this magnetic maximum (see Figure 11) obviously show the presence of a regional magnetic effect. This regional effect is probably due either to a change in the magnetic susceptibility of the basement rocks or to a major basement fault. Epicenters of small earthquakes lie in this area. For this reason the latter supposition may be preferable.

d. *The Igal Structure*

The second buried hill on the mentioned trend is the Igal structure (N46°32′ E35°36′). It is east of the deep basement depression indicated by the gravity

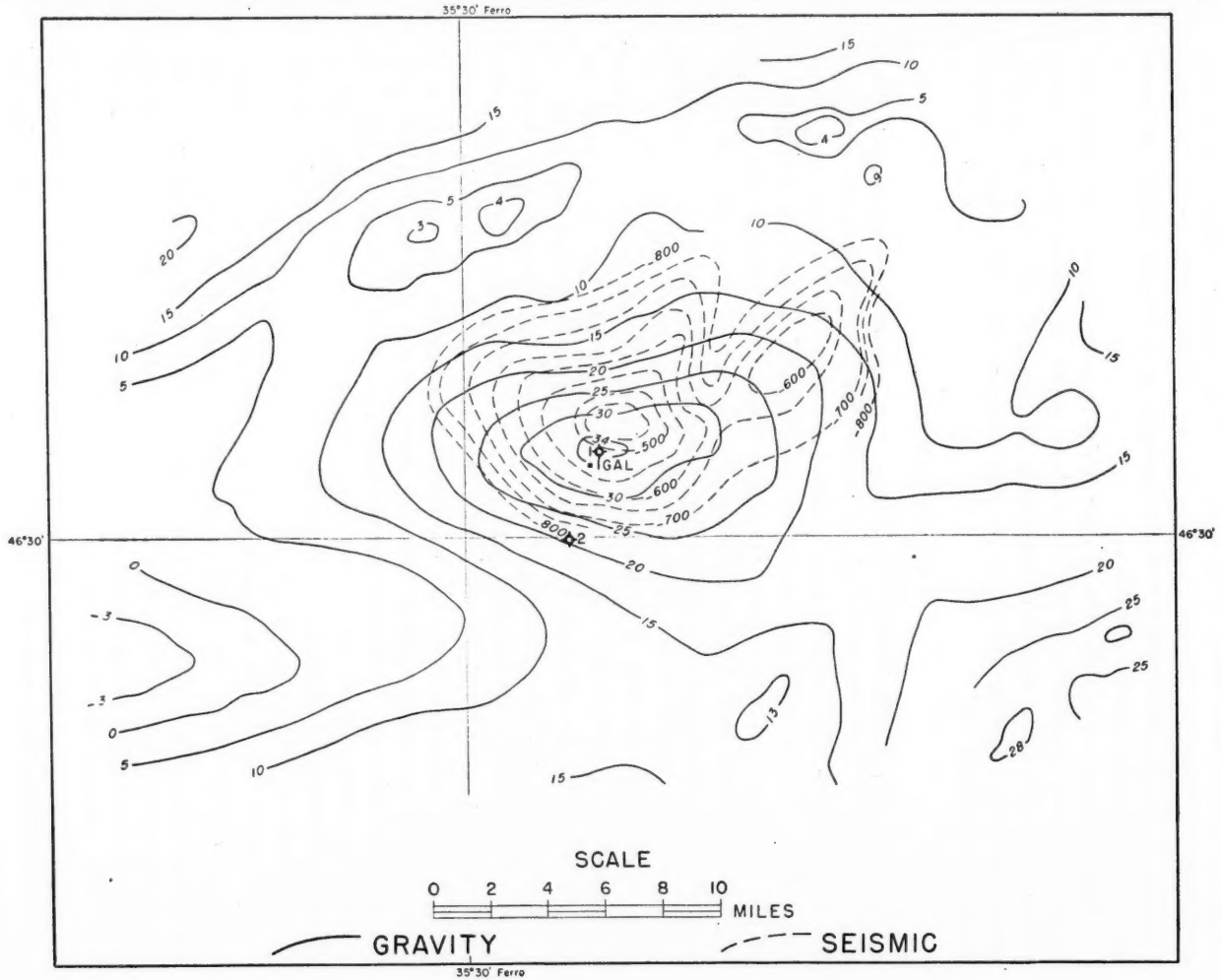


PLATE 12. Gravity and seismic map of the Igal structure.

minimum south of Marcali. This gravity maximum was also interpreted as a buried hill. The straight contours and pronounced corners of the gravity maximum indicate faulted structure. The seismograph survey confirmed this structure, though there is a considerable difference in the shape of the seismic structure and the gravity indication (see Plate 12). This is a rather hilly area and the reflections were in many instances poor, which may explain the discrepancies.

Two wells were drilled on this structure. The first well, at the top of the structure, hit Mesozoic limestone at 2,100 feet with a thin Miocene layer on the top similar to the Hahot structure. This well was abandoned as a dry hole. The depth to the Mesozoic formation is in very good agreement with the depth computed from the seismic reflections.

The second well, three miles south of Igal, at the south flank of the structure, was abandoned at 4,979 feet in tuffaceous sandstones and conglomerates directly underlying Miocene schlieren facies. This well had some oil shows in Pliocene marls and Miocene conglomerates.

e. *The Pincehely Structure*

Northeast of Igal a very sharp, angular gravity maximum indicates a shallow buried hill bordered by faults. (Gravity data not available. See Plate 3.) The high gravity values and especially the abrupt changes in the size and direction of the observed gradients suggest that the basement here is at a shallow depth, probably only a few hundred feet. Although the terrain conditions are unfavorable, the results of the torsion balance data indicate very distinctly the faults outlining this buried hill. No seismic survey was made on this prospect.

The magnetic data (Plate 2) show a magnetic minimum corresponding very closely to the gravity maximum at Pincehely. It may be interpreted that this buried hill consists of nonmagnetic rocks, most probably of limestones, surrounded by rocks with some magnetic susceptibility, perhaps clays and sandstones with some iron content.

f. *The Németkér Structure*

The observed gravity data (not available) show a gravity maximum at Németkér (N46°42′ E36°26′) which is separated only by a relatively small gravity minimum from the Pincehely gravity maximum. The Németkér gravity maximum is interpreted also as a buried hill structure. The top of this structure is, according to the seismic survey, at a depth of about 1,600 feet.

g. *The Kaposvár Structure*

A west pointing gravity nose, with some closures at the eastern end, was mapped near Kaposvár (N46°21′ E35°27′). A test well drilled west of Kaposvár encountered phyllite at 3,730 feet after penetrating Upper Pannonian (Pliocene) strata. No oil or gas show was observed and it was abandoned as a dry hole.

The Kaposvár structure is regarded as a buried hill. Only the northern slope

PLATE 12. Gravity and seismic map of the Igal structure.

of this structure is well developed; to the south it is pressed against a large basement block, which will be discussed later.

West of the Kaposvár structure a small gravity maximum indicates a small basement horst or a dome. No test was made on this prospect.

h. *The Döbrököz-Kurd Structure*

The Döbrököz-Kurd (N46°27′ E35°59′) structure is most probably a basement high. According to the magnetic anomalies, this structure contains a considerable amount of volcanic material. This is especially true for the eastern part of the structure.

The results of the seismic survey show five to ten degree dips in the sediments at the sides of this structure.

The gravity anomalies indicate a north-south striking fault at the west side of this structure.

Previous to the European Gas and Electric Company's exploration, a well was drilled by the Hungarian Oil Syndicate (A.I.O.C.) south of Kurd, on the south flank of the structure. This well was abandoned at 2,042 feet in Miocene. Some gas shows were found in the Pliocene formations and some oil traces in the Miocene. No further test was drilled on this structure.

i. *The Görgeteg Structure*

Southeast of the Inke structure a long north-south striking gravity maximum was found by the torsion balance survey. This maximum is separated from the Inke structure and from the Kaposvár structure by gravity minima with rather low (−10 and −9 milligals) gravity values. The seismograph survey made over the Görgeteg gravity maximum showed no reversal of the dips but only a uniform general southwest dip. No satisfactory explanation could be found for this discrepancy. A deep-seated basement horst, which is not reflected in the upper strata, may be supposed. The well drilled at the highest point of the gravity maximum was abandoned at 6,755 feet, still in Lower Pannonian. Very compact, heavy marls were found in great thickness in the lower section of the hole, the density of which reached 2.65. This means that the basement horst should consist of very dense rocks to produce sufficient density contrast to account for this gravity maximum.

A magnetic maximum partly coincides with the southern part of the Görgeteg gravity maximum.

Altogether, three holes were drilled along the gravity axis. They showed only insignificant differences in the structural position of the Pannonian strata. All three wells showed some oil and gas traces. The gravity terrace at the southeast side of the gravity maximum may have some importance, as it may reflect a corresponding subsurface structure favorable for trapping oil or gas.

j. *Remains of the Variscan Mountain System North of the Mecsek Mountains*

According to the gravity anomalies, the basement south of the Kaposvár and

Kurd structures and north of the Mecsek Mountains is at a rather shallow depth, probably above 1,000 feet. On the magnetic map, this area presents outstanding north-northwest south-southeast trending magnetic anomalies. It may be presumed that these anomalies are due to a remnant of the Variscan Mountain system* which served as a resisting block for the arching up of the Mecsek mountain and for the developing of the Kaposvár and Kurd structures on its north side. This block is marked on Plate 3.

Examining the magnetic map of this area, it can be noticed that the eastern part is greatly disturbed. Numerous indications of relatively small intrusions can be observed here. It is assumed that the eastern part of this Variscan block has fractured under great orogenic pressure from the south and shifted toward the north, with relation to the western part. This horizontal displacement took place along a fault running in the vicinity of Vasas (N46°08′ E35°59′), Komló and Dombovár (N46°22′ E35°48′) (see Plate 3). This horizontal displacement can be clearly observed in the Mecsek Mountains.[6] East of this fault, along a line parallel to it, several trachydolerite intrusions occurred which are indicated by the magnetic anomalies. Some of these now outcrop on the eroded surface.

The fractured eastern part of this Variscan block is penetrated with volcanic material, some of which probably reached the old surface by breaking through a fault south of the Kurd structure along a line parallel to the Kapos river.

The limited gravity survey made over the western part of the Variscan block suggests that this block was divided later into parts corresponding to the strike of the younger sediments.

4. *Structure of the Area South of the Mecsek Mountains*

The gravity anomalies indicate an east-west striking major fault or fault system south of the Mecsek Mountains. The downthrown side of this fault (or faults) is to the south. It is interesting to note that in the western part of the area the basement remained, in general, in a relatively higher position, while in the eastern part of the area it sank to a much greater depth. A fault system, following a zigzag pattern, separates these two areas.

In the western part of the area, shallow horsts interchange with deep, narrow grabens and form a rather intricate pattern as concluded from the gravity anomalies. Small, strongly faulted structures are present in this area.

The eastern part of the area seems to be less disturbed. Due to the relatively great depth of the basement, small basement horsts and grabens cannot be easily detected by the gravity survey. The only significant structure in this area is perhaps the dome, or horst, southwest of Szigetvar (N46°03′ E35°24′), indicated by a closed gravity maximum.

* The Variscan Mountain system, which undoubtedly crossed southwest Hungary, most probably had a north-northwest south-southeast strike here. It seems justifiable to call Variscan those masses which still show distinct characteristics of the Variscan Mountain system, and which did not take part in the latter orogenic movements, but acted as more or less resisting blocks and, even if they were dissected into various blocks, preserved their Variscan character. They differ from their refolded surroundings and for this reason can be distinguished from them.

The gravity anomalies suggest some faults along the Drava river. However, these anomalies may also be interpreted as the north flank of a large syncline.

The pattern of the magnetic anomalies in this area is rather interesting. Starting with the magnetic maximum at the southern end of the Görgeteg structure (Plate 2) and continuing with the long, east-west striking maximum south of Szigetvar and finally ending at the maximum indicating the crystalline core of the Mecsek Mountains, we find that these anomalies follow the outline of the Variscan block as indicated by the magnetic survey.

Several small magnetic maxima were found south of the Mecsek Mountains. They are probably related to volcanic intrusions.

5. *Structure of the Area Between Szekszárd and Mohács*

The geophysical data of this area are not now available. Only their interpretations are given on the schematic tectonic map on Plate 3.

In the area north and south of Szekszárd (N46°21′ E36°22′) the geological conditions are very complicated. Faults with various strikes and granite and trachydolerite masses with irregular shapes produce intricate subsurface conditions which are reflected by the gravity and magnetic anomalies. The outlines shown on the schematic tectonic map of this area indicate the contours of volcanic masses rather than real structures. The subsurface continuation of the Fazekasboda (N46°07′ E36°09′)-Morágy granite mountains is clearly indicated by the gravity anomalies.

Perhaps the only gravity maximum which corresponds to a structure of economic interest is north of Mohács (N46°00′ E36°20′). It strikes in a northeast-southwest direction. The south wing of the corresponding anticline is faulted and this fault can be observed on the surface. The torsion balance data indicate clearly an adjacent syncline northwest of this anticline.

South of Mohács, at Udvar, the torsion balance survey indicates the west end of a small fold.

6. *The Structure of the Area Southeast of the Velence Mountains*

a. *Variscan Block Southeast of the Velence Mountains*

The gravity and magnetic anomalies in the area southeast of Lake Velence, between Székesfehérvár (N47°12′ E36°05′)-Sárbogárd (N46°53′ E36°18′)-Dunapentele (N46°58′ E36°38′) and Pázmánd (47°17′ E36°20′) are different in character from the area south of Lake Balaton. It is assumed that this area consists of a rigid block which retained its Variscan structure, similarly to the block north of the Mecsek Mountains. Two major units can be distinguished within this block, as outlined on Plate 3. These probably consist of granite, similar to the granite of the Velence Mountains. The limited magnetic data indicate several volcanic intrusions. Basic igneous masses (pyroxene andesite) are known on the surface near the Velence Mountains. On the other hand, rhyolite was found at the surface east of Sárbogárd. This acidic rock showed no recognizable magnetic effect.

b. *The Adony Basin*

According to the gravity anomalies, the Variscan block described above is bordered on the east by a long, approximately north-south striking fault, with downthrown side to the east. East of this fault, and parallel to it, a gravity minimum indicates a deep basement trough. This trough ends in a round basin at Adony (N47°07′ E36°33′). The two gravity maxima at Baracska (N47°18′ E36°25′) and south of Adony may indicate a small dome and a small anticline, respectively. No seismograph survey was made in this area.

VII. CONCLUSION

The structure of those parts of southwest Hungary which are covered by thick young sediments, as reflected in the geophysical investigations of the European Gas and Electric Company [later called Hungarian American Oil Industrial Company, briefly MAORT, owned by the Standard Oil Co. (N. J.)], gives in many respects an entirely new picture of the subsurface geological conditions of this area. The question may be raised: How reliable are the geological conclusions drawn from the results of the geophysical investigations?

Geological structures concluded from geophysical data are naturally, in general, more or less hypothetical. Some of the structures detected in southwest Hungary by geophysical methods are proved by drilling (Mihályi, Igal) and in some cases the well data show a surprising agreement between the results of the torsion balance survey and the subsurface structure contour lines (Lovászi, Lispe).

The test wells drilled so far in southwest Hungary proved the interpretations of the gravity data to be essentially correct. The three wells drilled on the Görgeteg structure did not furnish conclusive information. The well data did not disprove the interpretations, and the discrepancy between the gravity and seismic indications in this area is still not explained. The same is true for the Salomvár prospect. These two are the only ones where the seismic data did not confirm the gravity indications.

Consequently, it may be supposed that the geological structures inferred from the geophysical data actually exist and correspond, at least in their main features, to the sketchy description and to the outlines drawn on the schematic tectonic map of southwest Hungary (Plate 3).

It is indeed remarkable how well the gravity anomalies reflect the subsurface conditions in southwest Hungary. The reasons for the success of the gravity method in this area were discussed in another paper and they should be repeated here. These are: (1) a considerable and progressive increase in density of the sediments from the surface to the pre-Tertiary basement; (2) absence of any sudden lateral density variation in the sediments; (3) absence of pronounced regional effects.

It may be worthwhile to summarize the scientific and practical results of the geophysical investigations in southwest Hungary:

(1) A schematic tectonic map of southwest Hungary mapping a great number

of subsurface structures of various types which were heretofore unknown.

(2) An accurate check of the relative pendulum stations with the gravity meter.

(3) A proof that the torsion balance can be successfully used even in hilly areas, if the topography consists of homogeneous formations and if adequate terrain corrections are applied.

(4) Discovery of the following oil and gas fields:

Field	Estimated Initial Recoverable Reserve	
	Oil, million bbls.	Gas, billion cu. ft.
Lispe, or Budafapuszta	30	54
Lovászi	35	87
Hahot	3.5	—
Ederics	?	25
Ujfalu	0.02	—
Mihályi	—	CO_2 for dry ice
Inke	—	? Natural gas with 30–50% CO_2
Total	68.5+	166+

In conclusion, the tectonic map mentioned above gives valuable information for future prospecting for oil by outlining the most important structural uplifts and showing their positions relative to the basins of the area.

VIII. ACKNOWLEDGMENTS

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A NEW INSTRUMENT FOR SEISMIC EXPLORATION AT VERY SHORT RANGES*

D. I. GOUGH†

ABSTRACT

An instrument is described for use in seismic investigation of subsurface structure to a maximum depth of about 100 feet. A hammer is used as source of seismic energy. A cathode-ray tube replaces the usual galvanometers as display device, and seismic arrivals are timed electronically by a modified radar technique. Only one seismometer is used, and travel times for different ranges are obtained by moving the hammer along the traverse line. Applications will lie mainly in the field of civil engineering. Field tests made at a dam site are compared with direct borehole tests of the subsurface structure.

INTRODUCTION

In the course of field work in the large-scale seismological program of the Bernard Price Institute of Geophysical Research, to which the writer is attached, it was noticed that the seismometers used were capable of recording footsteps at ranges of 100 feet or more. This fact led Dr. P. G. Gane, Deputy Director of the Institute, to suggest to the author that it might be worth while to try to exploit the possibilities of a hammer as a source of seismic energy for structural investigations at very short ranges, principally for civil engineering applications. After preliminary trials, suitable equipment was designed and made by the writer and tested at two dam sites in April–May, 1951. The tests appear to show that the instrument will be useful, at suitable sites, for the investigation of structure to a maximum depth of the order of 100 feet by the seismic refraction method of exploration.

The use of the seismic method for small-scale investigations of this type is not new (Current, 1943). Previous work has, however, all been done by means of conventional seismic equipment designed for use at long ranges, while the present equipment has been designed specifically for use at very short ranges. The advantages it possesses over the conventional method result from the convenience of the hammer as a source of seismic energy, from the application of the cathode-ray tube for display purposes, and from the use of radar techniques for timing the seismic arrival.

DESCRIPTION OF THE EQUIPMENT

Figure 1 shows the equipment, and Figure 2 is a block schematic diagram. The equipment includes the following parts:

(1) a hammer with inertia contactor, connected by cable to
(2) a timing unit;

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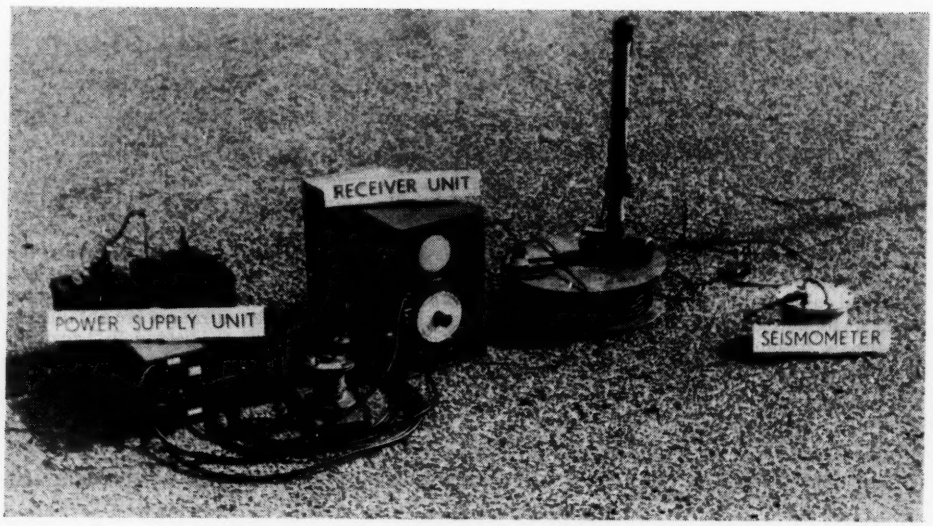

FIG. 1. The equipment.

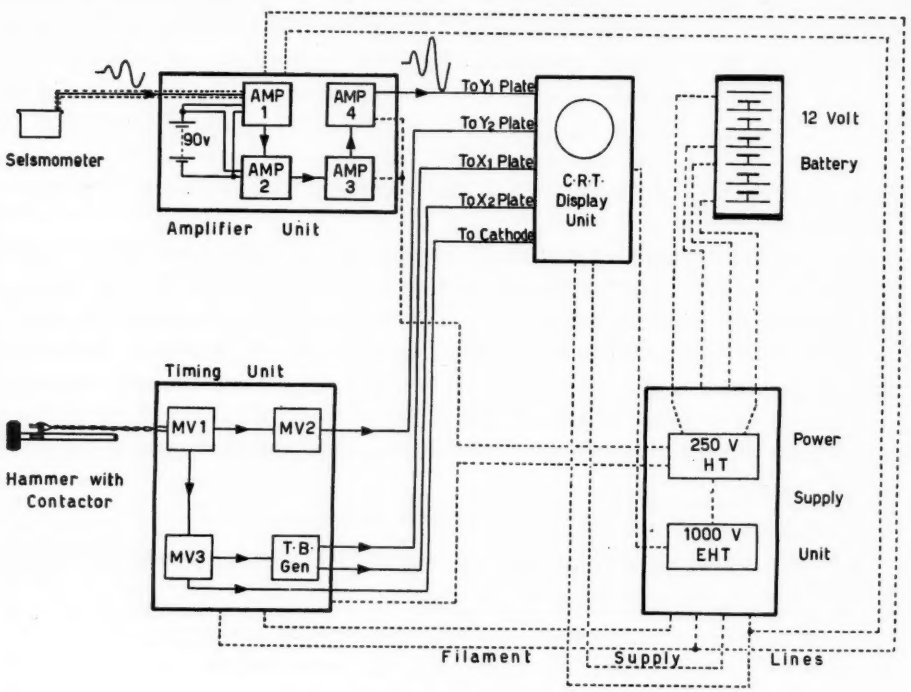

FIG. 2. Block schematic diagram of the equipment.

(3) a seismometer, connected by cable to
(4) an amplifier unit, internally connected to
(5) a display unit with cathode-ray tube;
(6) a power supply unit.

Parts (2), (4), and (5) are built into a single box, labelled "Receiver Unit" in Figure 1.

The Hammer with Inertia Contactor

The hammer is an ordinary ten pound sledge-hammer on a two foot wooden handle. The contactor is fixed on the handle a few inches from the head. No design of contactor that has been tried will for long withstand the stresses applied to it when attached to the head itself. The contactor consists of two flat springs of beryllium bronze carrying silver contacts normally separated by about 0.01 inch. When the hammer strikes the ground the upper spring bends under the inertia of its own mass and closes the gap. At the hammer-blow instant a positive voltage pulse of short duration is fed from this contactor to the trigger circuit. The input time-constants are so arranged that if the contactor closes more than once for a given blow, owing to vibration of the upper spring, only the first contact operates the trigger. The time delay before the contactor closes is a small fraction of a millisecond.

The Timing Unit

The units denoted MV in Figure 2 are all one-stroke multivibrators, each consisting of a double triode tube in the cathode-coupled multivibrator arrangement. The unit denoted TB Gen uses three tubes to generate and amplify a sawtooth voltage which is applied in push-pull to the X plates of the cathode-ray tube.

The sequence of events in the timing unit is indicated in Figure 3. When the hammer contactor closes, a positive voltage pulse triggers MV1, and the cathode potential drops. After a time determined by the coupling circuit, MV1 returns to its stable condition and the cathode potential returns to its former value. At the cathode of MV1 a negative square wave of voltage therefore appears. The coupling condenser and resistor of MV1 are variable and the duration of the square wave can therefore be varied continuously from about one to about 400 milliseconds.

The cathode of MV1 is coupled through short time-constant circuits to MV2 and MV3. Each of these multivibrators is arranged to trigger only from a positive pulse. Hence they do not trigger at the hammer instant when they receive a negative pulse from the cathode of MV1, but when MV1 returns ("flops") to its stable state both MV2 and MV3 operate.

MV3 gives a square wave of long, fixed duration, which is used as a "gate" pulse for the time-base generator. The spot therefore starts from the left side of the cathode-ray tube when MV3 "flips," i.e. when MV1 "flops."

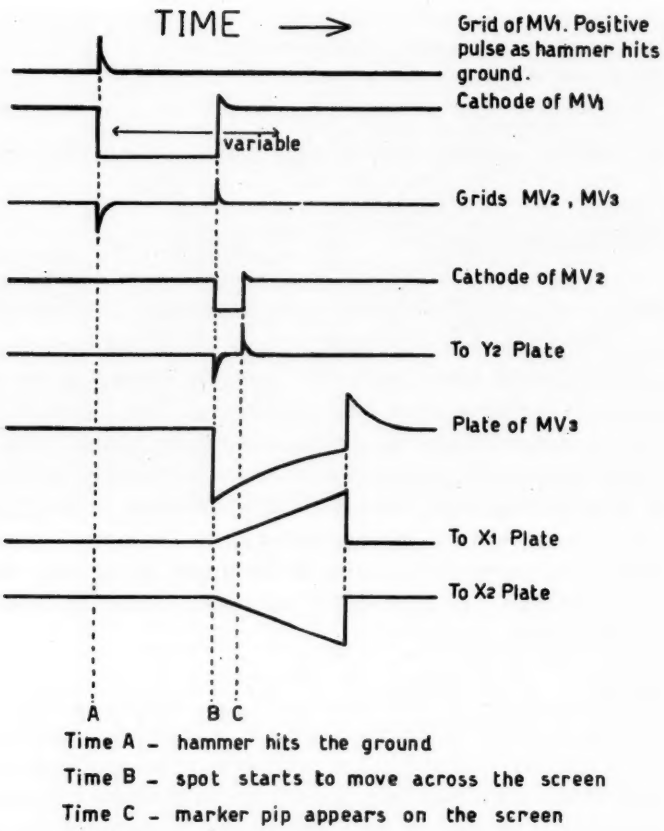
TIME
Grid of MV1. Positive pulse as hammer hits ground.
Cathode of MV1
variable
Grids MV2 , MV3
Cathode of MV2
To Y2 Plate
Plate of MV3
To X1 Plate
To X2 Plate
A
B C
Time A - hammer hits the ground
Time B - spot starts to move across the screen
Time C - marker pip appears on the screen

FIG. 3. Sequence of events in the timing unit.

MV2 gives a square wave of short, fixed duration (5.9 milliseconds). Its output is differentiated and applied to one Y plate of the cathode-ray tube. The spot is thus deflected downwards as it starts to move to the right, and upwards 5.9 milliseconds later. The upward spike is used as a reference marker on the trace.

The coupling components controlling the duration of the MV1 pulse are mounted behind the front panel of the receiver unit, and are controlled from the panel by switches and a large dial. These controls are calibrated in milliseconds *for the time interval AC* (see Figure 3), i.e. at any setting the time elapsing between the hammer blow and the marker pip can be read off the front panel directly. Suppose the seismometer output is connected to the Y1 plate. When the seismic wave reaches the seismometer, the spot will be deflected vertically. If the time AC is less than the seismic travel time, the wave will be seen to the right of the marker pip. By rotating the time calibrator dial between hammer blows, the wave is made to move to the left until it commences at the marker pip. The seismic travel time is now equal to the time AC and is read off the dial and noted.

A practised operator will require four to ten hammer blows to obtain the travel time for a particular hammer-seismometer distance. The timing dial covers four ranges, selected by switches:

Range 1: 7 to 25 milliseconds, reading to 0.1 msec.
Range 2: 25 to 43 milliseconds, reading to 0.1 msec.
Range 3: 10 to 210 milliseconds, reading to 1 msec.
Range 4: 200 to 400 milliseconds, reading to 1 msec.

This system of delaying the start of the spot for a variable time enables the operator to use a *constant time-base velocity* throughout a traverse. It has been found that the same seismic phase can be positively identified along a traverse in which the range varies from three to 250 meters. In an earlier model of the instrument the spot started to move at the hammer-blow instant, and the time-base velocity was diminished as range increased. It was impossible to identify a phase at widely different ranges, and hence the validity of travel-time curves was open to doubt. The device of delaying the start of the time-base to allow the use of a constant spot velocity is a vital feature of the design of this instrument.

The "gate" tube MV_3 supplies a brightening pulse to the cathode of the cathode-ray tube, so that the stationary spot between blows does not dazzle the operator and the fly-back trace is not seen.

A switch on the front panel reduces the bias on MV_3 and converts it into a free-running multivibrator. This provides a recurrent time-base for examining seismic noise waveforms.

Stability of the Timing System

It is necessary that the multivibrators MV_1 and MV_2 should give square waves of constant period for successive hammer blows and over a period of some weeks (i.e., between reasonably spaced calibration checks). Three types of variation are possible:

(1) Variation with temperature.
(2) Variation with HT supply voltage to the timing unit.
(3) Secular variation or drift.

(1) *Variation with temperature.* A complete calibration was carried out at 26.5°C. and repeated when the ambient temperature had been raised to 33.2°C. On the short-range there was no significant change. The long-range calibration showed a change of about 2 percent which may be significant but is near the setting accuracy of the dial. For variations of temperature likely to be encountered in the field it is not thought that the timing circuit has an appreciable temperature coefficient.

(2) *Variation with HT supply voltage.* Tests were made in which the battery supply to the motor generator was reduced from 12 volts to 10.5 volts, resulting in a drop in HT from 240 volts to 212 volts. There was no measurable change in the delay time (i.e. change less than 1 percent). Variations probable in the field will, therefore, not affect the timing accuracy appreciably.

(3) *Secular variation.* Complete calibrations were carried out separated by a month of field work with the instrument. The correction curves for these two dates are not significantly different and it is believed that a recalibration once a month will suffice to check field results adequately.

The timing circuits were calibrated in the laboratory against a beat-frequency oscillator.

The Seismometer

The seismometer was made for the experimental project but has no unusual features. It is a vertical-component moving-coil instrument of undamped natural frequency 29 cycles/sec and of robust construction, so that it withstands mechanical shock and can be transported unclamped. Damping is electromagnetic. The sensitivity requirement is that seismic noise at the quietest site shall give an output from the seismometer greater than the circuit noise from the amplifier. The seismometer must be connected to the amplifier by shielded cable, as an unshielded cable picks up an induced voltage surge from the hammer cable when the contactor closes.

The Amplifier

The amplifier comprises four stages of voltage amplification in series. The stages marked AMP 1, 3 and 4 in the block diagram are conventional pentode amplifiers of the resistance-capacity coupled type. Stage AMP 2 is a tuned amplifier stage using a double triode tube and a resistance-capacity bridge. Frequency and selectivity are both variable. A switch selects tuned or untuned amplification.

As indicated in Figure 2, Stages 1 and 2 are supplied with HT by a built-in 90 volt dry battery, to minimize noise and prevent oscillation. Stages 3 and 4 use the 250 volt supply common to the rest of the equipment. It will be observed that the amplifier does not use the same filament supply cells as the timing unit.

The amplifier is carefully shielded from the timing unit and from the display unit, in the receiver unit. In addition, Stages 1 and 2 are carefully shielded from Stages 3 and 4, to prevent oscillation. No trouble has been experienced with oscillation, in spite of the fact that the amplifier has an over-all voltage gain of 5×10^6 when untuned. A manual gain control is located at the input to AMP 2. The gain has proved to be adequate. Seismic noise at the quietest sites is about 1 cm in double amplitude on the screen, and full gain has occasionally been used at extreme ranges.

Automatic gain control was built into an earlier model of the amplifier, but it did not prove advantageous and has been dropped. Experience has shown that the tuned amplifier stage included in the present equipment is of little or no assistance, and it would be omitted from any future model.

The controls of the amplifier are mounted on a recessed panel on the left side of the receiver unit (see Fig. 1). The operator manipulates the amplifier controls with his left hand while his right hand sets the timing controls.

The Display Unit

This unit occupies the upper half of the receiver unit chassis. It contains the cathode ray tube, a bleeder circuit for supplying appropriate voltages to the various electrodes, brightness and focus controls, and coupling circuits to the plates. Since the tube filament supply is drawn from the lead accumulators, at ground potential, positive HT is used. Consequently the deflector plates are returned to +1,000 volts and high-voltage condensers must be used for coupling to the plates.

Trouble was experienced with electrostatic charge accumulating near the screen owing to insufficient return path for the beam electrons to the anode. This effect may be associated with the use of positive HT. It was cured by coating the outside of the tube, excluding the front three inches, with graphite paint and connecting the coating to the final anode. The beam current returns through the glass to this coating. For the protection of the operator, the graphite coating has been covered with an insulating layer.

The tube in use is a standard commercial type and is rated at 1,200 volts. It is operated at 1,000 volts. The screen is of long-afterglow type, which assists the operator to set the timing dial with the smallest number of hammer blows.

The Power Supply Unit

The power supply unit is housed in a small box separate from the receiver unit. It draws power from four tappings on a 12-volt lead accumulator and supplies filament current to the three sections of the receiver unit, 250 volts DC to the amplifier and timing units, and 1,000 volts DC to the display unit. It is conveniently described in two parts, though these parts are built together on the same chassis.

(a) *The 250 volts supply* is drawn from a small motor generator which supplies 250 volts from 12 volts input. The output is thoroughly smoothed and passed to the receiver unit.

(b) *The 1,000 volt supply* is provided by a free-running multivibrator, one plate load of which is a choke. When the current through this choke is cut off at the end of each cycle, di/dt is large and a large voltage surge Ldi/dt appears across the choke. This surge passes through a high voltage selenium rectifier to a storage condenser. After a large number of cycles this condenser accumulates a charge giving a supply of not more than 500 microamps at 1,000 volts. The voltage is adjusted by means of a potentiometer which varies the frequency of oscillation of the multivibrator. The bleeder network in the display unit is of high resistance (30 megohms) and the source has only to supply a current of 150 microamps.

In addition to the HT and EHT supplies, the power supply unit distributes the appropriate filament supplies to the sections of the receiver unit. One cable terminating in clips connects it to the battery, and three cables connect it to the amplifier, display unit, and timing unit respectively.

The entire equipment draws about 4 amps from each half of the 12 volt battery and therefore dissipates about 50 watts of power. The battery runs the equipment for two normal field days before being recharged.

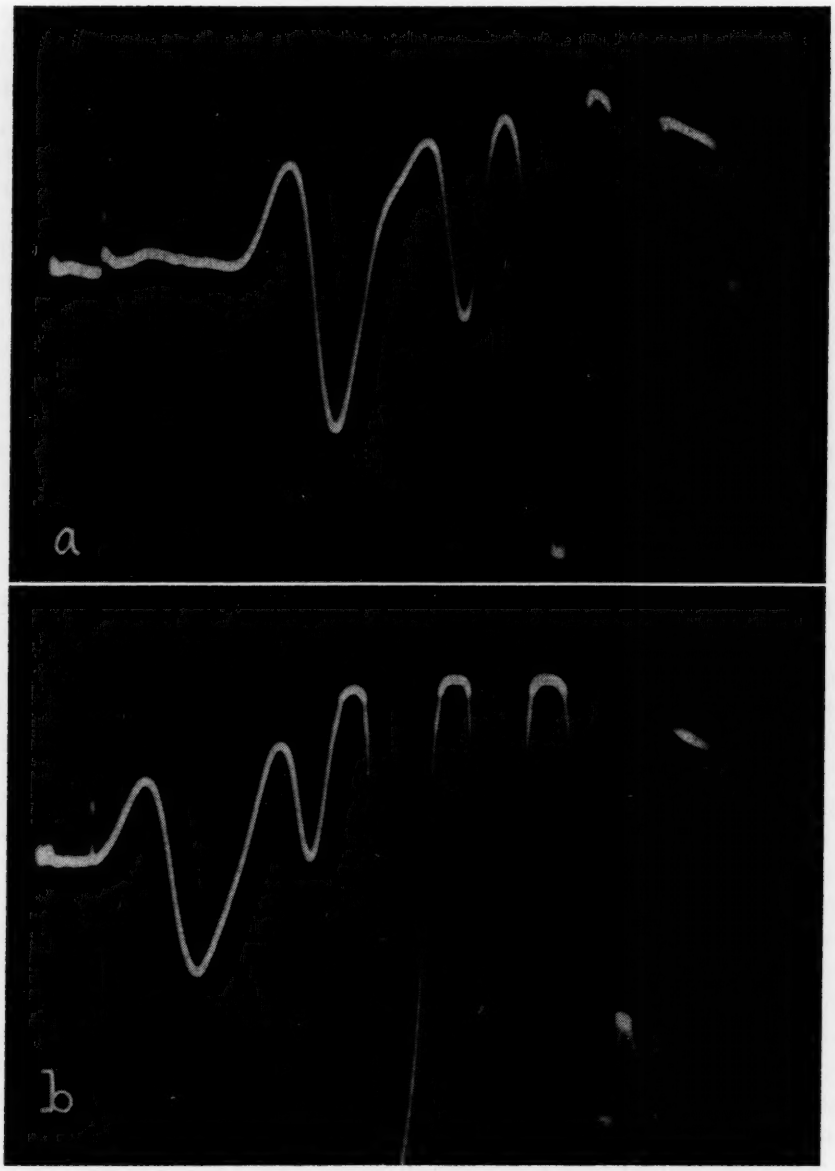

FIG. 4. Appearance of the wave on the cathode-ray tube screen. (a) The seismic arrival is later than the marker pip. (b) The timing dial has been rotated to bring the first arrival to the marker pip.

FIELD TESTS OF THE EQUIPMENT

Procedure in the Field

The procedure in the field has been as follows. A line is selected for the traverse. The seismometer is buried about 100 feet away from the receiver unit to avoid interference from movements at the receiver. The traverse is measured out by steel tape, markers being placed at predetermined distances from the seismometer. The operator sets the gain at minimum and asks the hammerer to start at the smallest range (usually 3 to 5 meters from the seismometer). He turns the timing dial until the pip coincides with some well defined phase of the seismic wave (usually the first negative peak). Figure 4 shows the appearance of the seismic wave on the screen.

The operator now reads the timing dial and signals to the hammerer to move on to the next range marker. He now sees the seismic wave displaced to the right of the pip, and turns the dial to bring it back to the same relative position as before. He reads the travel time and again signals to the hammerer to move on. This procedure is repeated until the traverse is complete.

The method of increasing range ensures that the operator becomes thoroughly familiar with the appearance of the wave at short range, where noise is not visible, and can recognize the same wave in noise at large ranges. When he is looking into the cathode-ray tube hood he cannot see the timing dial, and settings are not, therefore, influenced by any expectation he may have, e.g., of linearity of travel-time curve.

As the range increases, the gain control is advanced so as to keep the apparent amplitude of the wave approximately constant. Ranges are chosen to give roughly equal time increments, i.e., stations are closely spaced near the seismometer where velocities are low and widely spaced at large ranges where incremental velocity is high. Typical spacing would be:

1 meter intervals	from $x=$	3	to $x=$ 10 meters
2.5 meter intervals	from $x=$	12.5	to $x=$ 30 meters
5 meter intervals	from $x=$	35	to $x=$ 60 meters
10 meter intervals	from $x=$	70	to $x=$ 140 meters
20 meter intervals	from $x>$	160 meters	

A typical long traverse extended from $x=3$ to $x=246$ meters and t was read at 33 stations, i.e., for 33 values of x. In another typical traverse, the number of hammer blows per station varied from 4 to 20, the mean being 6.6 blows per station. A long traverse therefore requires about 220 hammer blows.

Whenever the truck can reach the site, the receiver unit, power supply unit, and batteries are kept in it. The equipment can be moved from the truck in two loads each for two men. The major part of the weight is contributed by the batteries.

Regarding a traverse to maximum range 250 meters as a "long traverse," and a traverse to 80 meters as a "short traverse," it has been found that four long

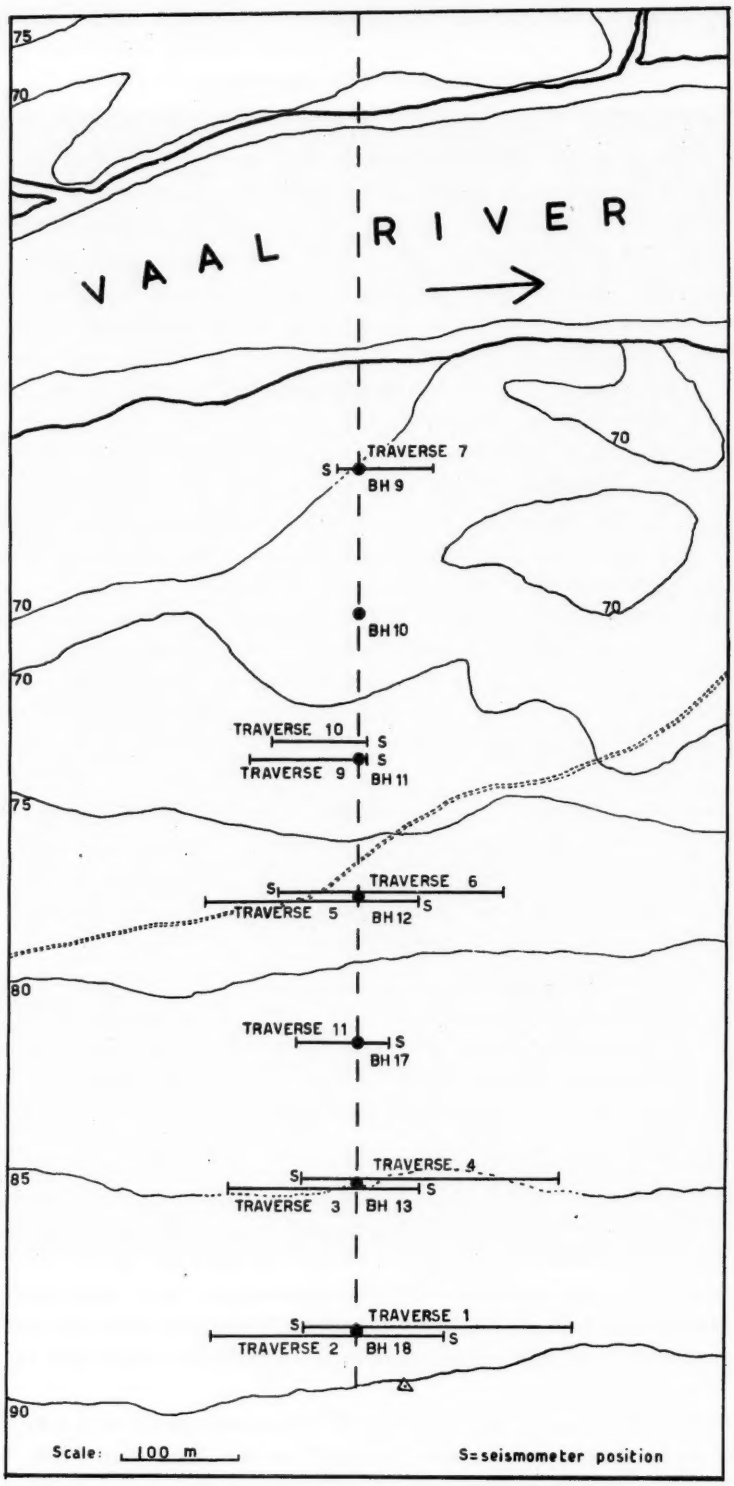

FIG. 5. The site of the field tests at Kromellenboog.

traverses or six short traverses form a fairly heavy day's work. Short traverses are often sufficient where one is interested only in shallow structures, down to say 30 feet. It has been found possible to plot a day's travel time curves in the evening and make a provisional graphical solution. This is important, as it makes possible the planning of the next day's work. Occasionally where unusual travel times are found, a travel-time curve is plotted roughly before making the next traverse.

Field Tests at Kromellenboog

When local field tests had shown that the instrument was performing reliably, it was decided to give it a series of tests at a site where drilling had already given an indication of the subsurface structure. For this purpose a projected dam site on the Vaal River, at Kromellenboog in the south-west Transvaal, was selected. Boreholes have been drilled on both banks at points along two straight lines across the river. The work here reported was located so as to give comparison of the seismic depths found with depths indicated by the boreholes on the north-west bank along the longer of the two lines of boreholes.

As indicated by the boreholes and by surface observation, the structure is of two general types. On the high ground further from the river, solid Ventersdorp lava is overlaid by more or less broken decomposed lava, and this in turn by highly compacted soil. On the lower ground near the river, in what is believed to be an old bed of the river, solid lava is overlain almost directly by relatively uncompacted river sand and soil, the intervening layer of broken lava being generally thin.

Traverses were generally located so that the line of traverse passed through a borehole, and was at right angles to the line joining the boreholes. Traverses were thus parallel to the river bank. The seismometer was placed from 10 to 70 meters upstream or downstream from the borehole, so as to make the comparison between borehole and seismic depths as valid as possible. In some cases traverses were made in both senses, in others in only one sense. Altogether 10 useful traverses were made, of which 8 give comparisons with 7 depths in 6 boreholes. Figure 5 shows a sketch map of the site, with the positions of the various traverses.

The First Type of Structure

On this fairly hard surface it was found that P waves were clearly visible and the first arrival could be followed to maximum ranges of 250 meters. In soft patches it was advantageous to hit stones embedded in the soil rather than the soil itself. The limit was set by the ratio of hammer wave to seismic noise, this ratio being about 2 to 4 at the maximum ranges used. It is possible that ranges of 300 meters could have been attained at some of the sites.

In all of this work, as well as at Bronkhorstspruit, the first arrival showed remarkable constancy of form, being clearly identifiable along the traverse. No

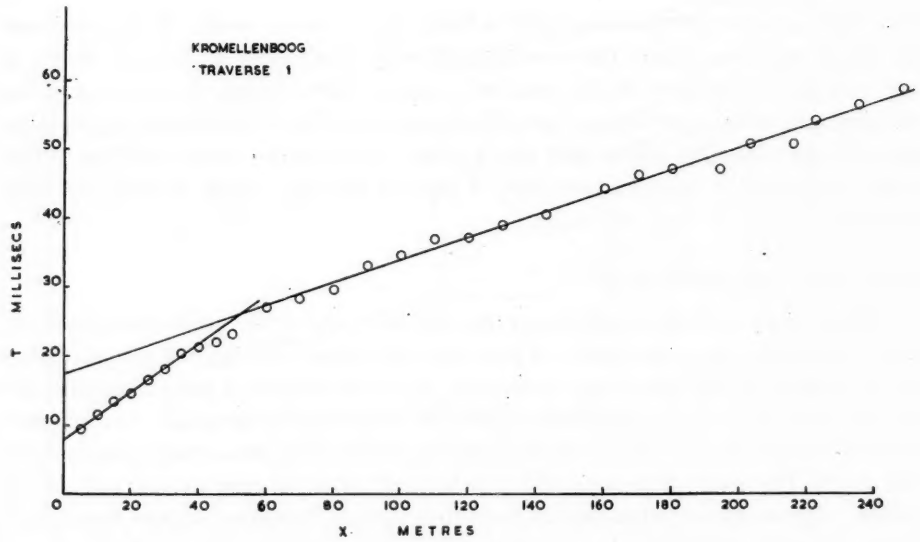

FIG. 6. Travel time diagram, Kromellenboog.

travel-time was accepted unless the same phase had been definitely identified and set in coincidence with the marker. It was found that the easiest phase to set on the marker was the first negative peak. Repetition for successive hammer blows at a given range was good. It is believed that the scatter in t shown by most travel-time curves is practically all due to structural irregularities in the rock. The excellent repetition obtained on one traverse at Bronkhorstspruit lends support to this view. The frequency of waves decreased gradually with increasing

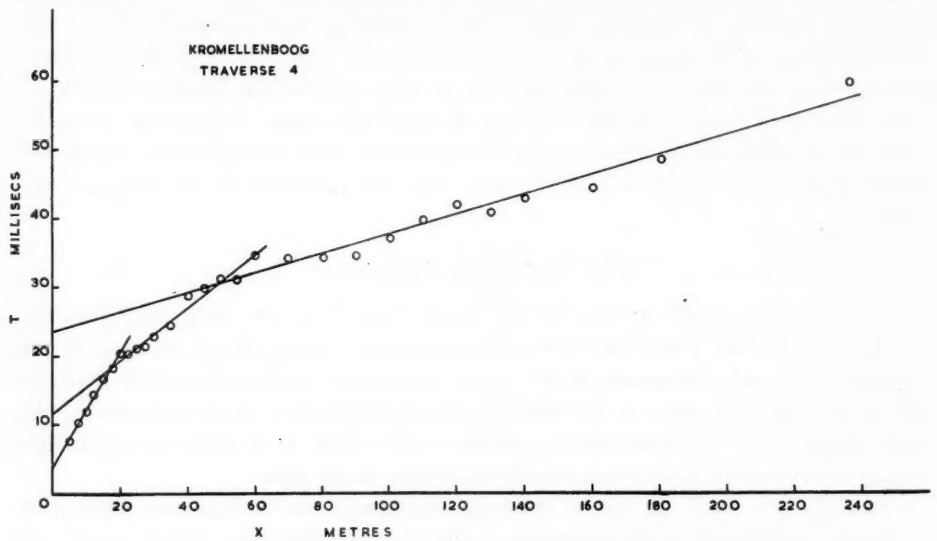

FIG. 7. Travel time diagram, Kromellenboog.

range, though the general appearance remained unchanged. A representative frequency would be 80 to 100 cps.

Figures 6 and 7 show typical travel-time curves for this Type 1 structure at Kromellenboog. Certain points are apparent:

(a) There is a considerable positive intercept on the t axis. Part of this intercept is due to setting the marker not on the first arrival, but on the first negative peak. This should give an intercept of about 3 millisecs. The observed intercepts are always 3 millisecs or more. Where the intercept is greater than 3 millisecs, it is thought to be due to a thin layer of aerated soil in which the seismic velocity is very low (Lester 1932). This layer is thought to produce the observed time delay while being too thin to be visible on the travel-time diagram.

(b) The points show considerable scatter in time from any simple line or lines. This scatter is believed to represent irregularities in the interfaces between layers of different velocities, or in the elastic constants of one or more of the media, or both. In other words, the failure of the points to fit a simple curve or set of lines is due to the departure of actual conditions from the ideal model giving that simple curve or set of lines. It will be shown below that the repetition of the instrument excludes observational error as a major cause of this scatter.

(c) While it is true that the scatter in t shows that the structure is not simple, it is nevertheless possible to fit a simple curve or set of lines which will give the "large-scale" structure upon which the irregularities are superimposed. The selection of a curve or set of lines to fit the points is the chief problem of interpretation, which will sometimes prove insoluble. In all cases at Kromellenboog sets of straight lines appeared to give the best fit. This corresponds to a number of homogeneous media lying upon one another. From the velocities, i.e., from the slopes of the straight lines, some idea of the nature of the medium (solid rock, broken rock, soil) can be deduced, and from the time intercepts the depths of interfaces can be found, either by assuming the interfaces are horizontal or else by using traverses in both senses to determine the dip.

Applying the interpretation of two straight lines to Traverse 1 (Fig. 6), we find a layer of velocity 2.9 km/sec covering a medium of velocity 6.0 km/sec. The depth of the interface is calculated as 52 feet. The velocities are attributed to broken lava and solid lava respectively, the soil being apparently too shallow to be seen. The borehole here gives depths of 9 feet for the soil and 44 to 57 feet for the top of the solid rock.

As shown in Figure 7, Traverse 4 gives larger scatter for the rock lines. Taking the interpretation given, we have:

$v_0 = 1.2$ km/sec (soil) underlain by

$v_1 = 2.6$ km/sec (broken rock) underlain by

$v_2 = 7.0$ km/sec (solid rock)

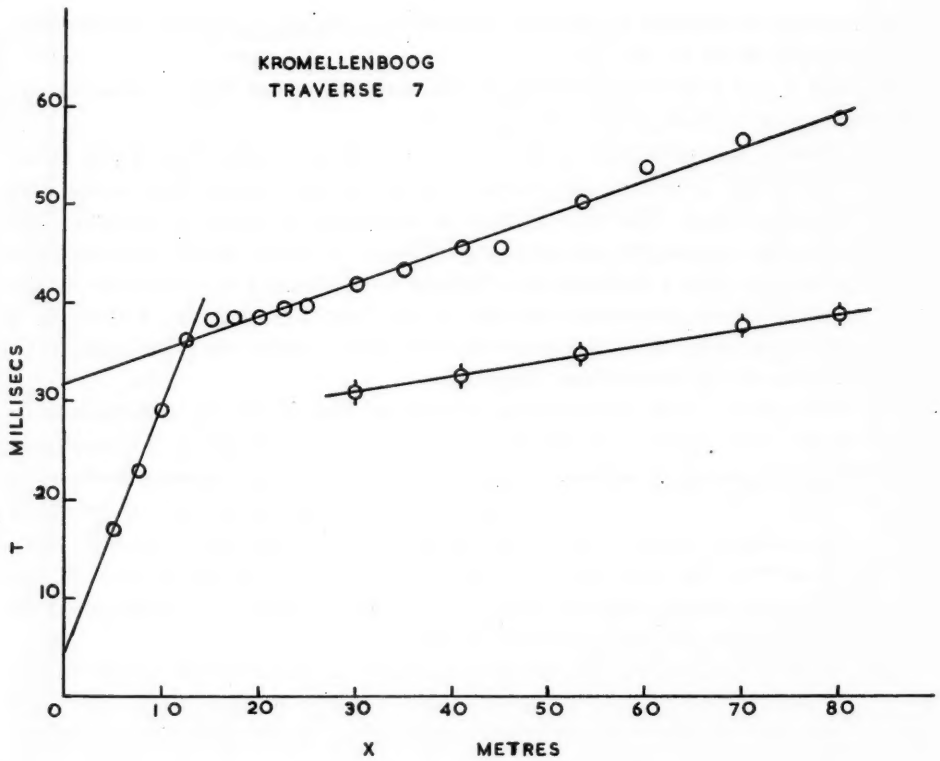

FIG. 8. Travel time diagram, Kromellenboog.

the interfaces being at depths 17 feet and 69 feet respectively. The borehole here gives depths 30 feet and 60 to 71 feet respectively.

Traverses 1, 2, 3, 4, 5, and 11 were made on the Type 1 structure, and the results deduced from their travel time curves are given in Tables 1 and 2. In making comparisons between seismic depths and borehole values, it is important to remember that seismic refraction depths are averaged over 50 to 100 meters horizontal extension, whereas a borehole gives a spot depth.

The Second Type of Structure

On the river soil the surface was softer and it was at times difficult to get the contactor on the hammer to close. It was found that the P wave was very small and could not be used. The *S* waves were, however, large and successful depth determinations were made using them. Figure 8 shows the travel-time curve from Traverse 7. The lower straight line represents the velocity of *P* waves in the underlying solid lava, the five points defining it having been obtained by very hard hammering. This line confirms that the upper straight line represents an *S* wave velocity. As shown in Table 1, the velocities are 6.39 km/sec and 2.93 km/sec. The velocity ratio is thus 2.18, which is of the right order of magnitude.

TABLE 1

SUMMARY OF RESULTS OF WORK AT KROMELLENBOOG DAM SITE
MARCH–APRIL, 1951

Traverse No.	Largest Range Meters	No. of Points	Interpretation	P Wave Velocity km/sec.			S Wave Velocity km/sec.		Depth of Seismic Discontinuities Feet	
				"Soil"	"Broken lava"	"Solid lava"	"Soil"	"Solid lava"	1st	2nd
1	244	28	2 str. lines	—	2.9(2)	6.0(1)	—	—	—	52
2	212	26	2 str. lines	—	3.9(6)	6.4(1)	—	—	—	61
3	175	22	3 str. lines	1.45±0.11	2.62±0.25	8.94±0.76	—	—	22	77
4	236	28	3 str. lines	1.19±0.02	2.60±0.22	6.99±0.44	—	—	17	69
5	193	27	4 str. lines	—	2.58±0.46	7.41±0.08	—	—	—	27
6	202	27	Doubtful	—	—	—	—	—	—	—
7	80	17	2 str. lines	—	—	—	0.40±0.01	2.93±0.10	18	—
	80	5	1 str. line	—	—	6.39±0.22	—	—	—	—
9	98	18	2 str. lines	—	—	—	0.40±0.02	2.78±0.18	19	—
10	79.5	15	2 str. lines	—	—	—	0.6	2.41	11	—
11	80	17	2 str. lines	0.67±0.02	—	5.44±0.32	—	—	26	—

Remarks. In Traverses 1 and 2, the soil was too shallow to appear on the travel-time diagram. Traverse 6 gave a very irregular travel-time diagram, and no interpretation could be made.

It will be seen that the travel-time curve of Figure 8 again shows a positive time intercept. Scatter of the points in time is less pronounced than for the Type 1 structure. It is suggested that this corresponds to smoothing of the lava surface due to erosion by the river in the past.

There appears to be little doubt that the two straight lines as drawn fit the observations. They give a velocity of 0.40 km/sec underlain by rock of velocity 2.93 km/sec. These velocities are reasonable as *S* wave velocities in soil and solid rock respectively. There is no sign here of broken rock. This agrees with the borehole, which gives a thickness of only 4 feet of broken lava. The seismic depth of 18 feet compares with the borehole depth of 19 to 23 feet.

Traverses 7, 9, and, 10 refer to Type 2 structure. The results are given in Tables 1 and 2.

TABLE 2

COMPARISON BETWEEN SEISMIC DEPTH AND BOREHOLE DATA

Traverse No.	Borehole No.	Depth in Feet to Bottom of				Wave Type
		Soil		Broken Lava		
		Seismic	Borehole	Seismic	Borehole	
1	18	—*	9	52	44–57	P
2	18	—*		61		P
3	13	22	30	77	60–71	P
4	13	17		69		P
5	12	—*	8	27	21–24	P
7	9	18	19	(18)†	23	S
9	11	19	16	(19)†	18	S
11	17	26	20–24	(26)†	24–30	P

* Soil too shallow to be seen.
† Broken lava too thin to be seen.

Precision of Depth Determinations

It is of some importance to form some idea of the order of accuracy of depth determinations from such traverses as those described above. An estimate has been made, as follows. The points of the travel-time plot are classified as belonging to a number of groups, each defining a straight line. For each group of observations a straight line is now fitted by the method of least squares. The least squares solution gives the slope of the line, with its standard error, and its intercept on the time axis, with its standard error. Thus for the two-medium seismic refraction case, it is easy to obtain the velocities in the two media with their errors, and the difference t_{i_1} between the two intercepts on the time axis, with its error. That is, we have $v_0 \pm \Delta_0$, $v_1 \pm \Delta_1$ and $t_{i_1} \pm \Delta_t$. In terms of these parameters, the thickness of the upper medium is

$$Z_0 = \tfrac{1}{2} t_{i_1} \cdot v_1 v_0 / \sqrt{v_1^2 - v_0^2}$$

or

$$Z_0 = F_0(t_{i_1}, v_1, v_0). \tag{1}$$

In the same way, the thickness of the second layer in the three-medium case is

$$Z_1 = F_1(t_{i_2}, t_{i_1}, v_2, v_1, v_0) \tag{2}$$

and the standard errors of the independent variables can be obtained from least-squares solutions.

It can be shown (Brunt 1931, p. 48), by means of Taylor's expansion, that if $P = f(m_1, m_2, m_3 \cdots m_n)$ where m_s has standard error r_s, then the standard error of P is R where

$$R^2 = \sum_1^n \left(\frac{\partial f}{\partial m_s}\right)^2 \cdot r_s^2. \tag{3}$$

Application of equation (3) to the depth formulae (1) and (2) thus gives the standard error of the layer thickness in terms of the partial differentials of the expression for the depth, and the standard errors of the velocities and intercept times.

This method has been applied to Traverses 4 and 7 at Kromellenboog. The travel-time diagrams are given in Figures 7 and 8. For Traverse 4, the least-squares solutions give

$$v_0 = 1.19 \pm 0.02 \text{ km/sec.}$$
$$v_1 = 2.60 \pm 0.22 \text{ km/sec.}$$
$$v_2 = 6.99 \pm 0.44 \text{ km/sec.}$$
$$t_{i_1} = 7.8 \pm 1.5 \text{ millisec.}$$
$$t_{i_2} = 19.7 \pm 1.4 \text{ millisec.}$$

Application of the above theory gives for the thicknesses of the first and second layers,

$$Z_0 = 5.2 \pm 1.1 \text{ meters},$$
$$Z_1 = 15.8 \pm 3.2 \text{ meters},$$

and the depths are

$$\text{Depth to "broken rock"} = 17 \pm 4 \text{ feet}$$
$$\text{Depth to "solid rock"} = 69 \pm 11 \text{ feet}.$$

For Traverse 7, we have

$$v_0 = 0.40 \pm 0.01 \text{ km/sec.}$$
$$v_1 = 2.93 \pm 0.10 \text{ km/sec.}$$
$$t_{i_1} = 27.7 \pm 0.9 \text{ millisec.}$$

which gives $Z_0 = 18.4 \pm 0.8$ feet. Here the uncertainty in the depth is much smaller, as might be anticipated from the travel-time diagram.

The range of uncertainty in the depth determination, as here calculated, is thought to give some indication of the departure from flatness of the boundaries, or of the inhomogeneity of the media, or both. It does not, of course, give any criterion of the correctness of the "interpretation," which consists in the original classification of observations into groups before making least-squares solutions.

Wavelength and Resolution

The wavelengths for a 100 cps wave range from 4 meters for the S velocity in soil to 60 meters for the P velocity in rock. It is surprising that depths within a wavelength of the surface are determined with the accuracy indicated above. The following consideration may explain the high resolution. At the commencement of the first arrival there are Fourier components of high frequency present. When one sets the marker on the first negative peak one may, therefore, in effect, be using the short waves associated with these high frequency components in order to secure higher resolution than would otherwise be possible.

Tables 1 and 2 summarize the results obtained in the field tests at Kromellenboog.

It will be seen in Table 1 that the velocities found for solid lava vary over a wide range and are frequently very high. These velocities are not regarded seriously as determinations of the rock velocity, because a very slight local dip of the interface will give a large effect on velocity where a high-velocity medium is overlaid by a medium of very low velocity.

Field Tests at Bronkhorstspruit

It had been hoped to compare seismic depths with borehole indications in the same way as at Kromellenboog, but blasting operations at this site had cov-

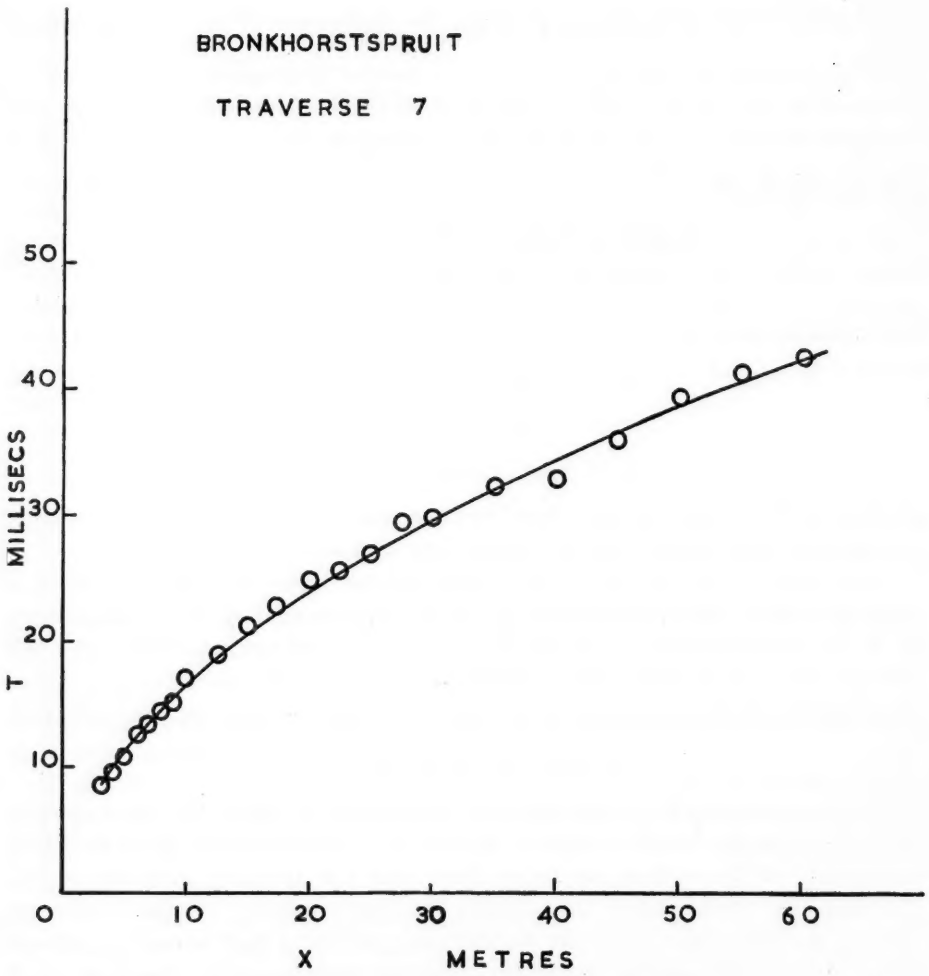

FIG. 9. Travel time diagram, Bronkhorstspruit.

ered the boreholes under many tons of rock. A number of test traverses were made in another part of the valley, however, and two travel-time curves are reproduced. There is less scatter in t than at Kromellenboog, suggesting that the structure approximates more nearly homogeneous media with plane boundaries.

Figure 9 shows the travel-time curve from Traverse 7. This is the only case found in which the observations are better fitted by a smooth continuous curve than by a set of straight lines. The curve drawn is the least-squares parabola. The velocity increases from 0.6 km/sec at $x=3$ meters to 2.5 km/sec at $x=50$ meters. The parabolic travel-time curve corresponds to a medium in which seismic velocity increases with depth according to a linear law,

$$v = v_0 + kz.$$

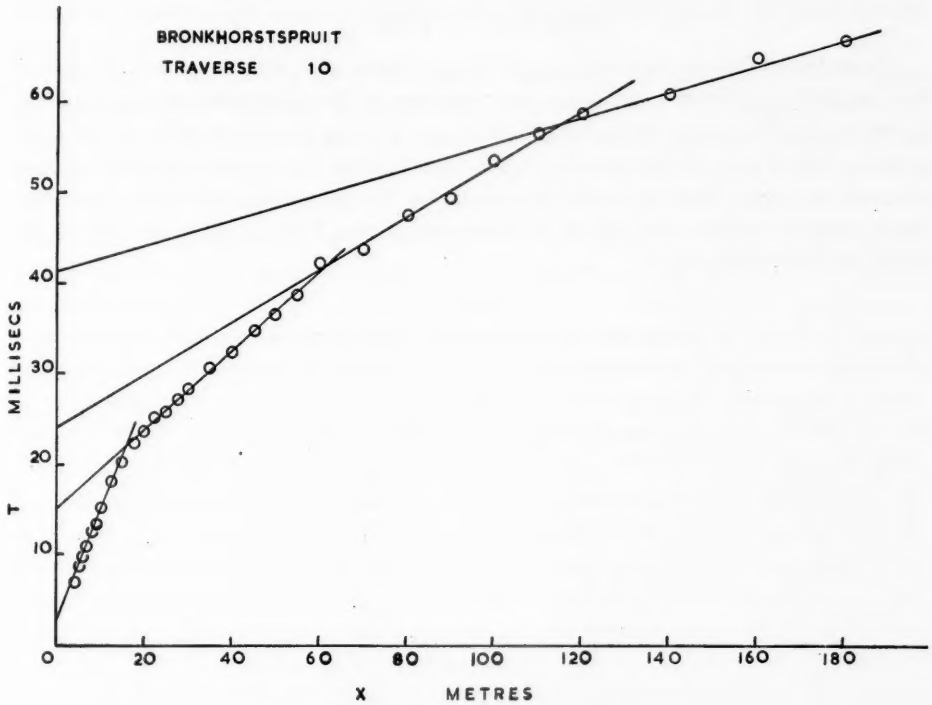

FIG. 10. Travel time diagram, Bronkhorstspruit.

The constant k for the parabola fitted to Traverse 7 is 0.57 km/sec per meter. The interpretation here is that the formation is not separable into discrete layers but changes its elastic properties continuously with depth (Ewing and Leet, 1932).

Figure 10 shows the travel-time curve from Traverse 10. This is one of the clearest examples obtained of observations fitted by a set of straight lines. The lines as drawn indicate:

$v_0 = 0.8$ km/sec to depth 18 feet;

$v_1 = 2.3$ km/sec to depth 60 feet;

$v_2 = 3.4$ km/sec to depth 154 feet;

$v_3 = 7.1$ km/sec below 154 feet.

v_3 is determined by only four points and is not highly accurate. Its value is reasonable for solid rock, as is the value of v_0 for surface soil. The nature of the two layers intervening between the surface soil and the solid rock is unknown. Since errors accumulate when depths are calculated for multiple layers, the last depth given may be considerably in error.

None of these seismic depths is subject to independent check.

Repetition of a Traverse

In order to obtain an estimate of the precision with which values of t would be repeated on different occasions, one traverse at Bronkhorstspruit was covered twice, on April 21, 1951 and on April 28, 1951. During the intervening seven days a heavy fall of rain occurred, and on the second date the topsoil was still damper than on the first. This probably accounts for the fact that arrivals are consistently about a millisecond earlier on the second date. Table 3 gives an idea of the precision of repetition:

TABLE 3

REPETITION OF A TRAVERSE ON DIFFERENT DATES

x meters	t millisecs		Δt millisecs.
	April 21, 1951	April 28, 1951	
12.5	19.1	18.1	+1.0
15	21.6	20.8	+0.8
17.5	22.6	21.7	+0.9
20	23.8	23.3	+0.5
22.5	25.4	25.0	+0.4
25	27.2	25.8	+1.4
27.5	27.9	27.2	+0.7
30	29.2	28.2	+1.0
35	30.6	29.7	+0.9
40	32.0	31.3	+0.7
45	35.8	35.8	0.0
50	38.4	37.4	+1.0
55	40.4	39.4	+1.0
60	41.6	41.4	+0.2
	Mean $\Delta t = +0.75$ msec.		

The values of Δt as shown give for the standard error of an observation 0.36 millisec. From the repetition here obtained, it appears, therefore, that the chance that a reading on the short-range dial will be in error by 1 millisec. is about one percent. This would appear to be proof of the correctness of the claim that scatter in t of the order of one or more millisecs is a true indication of departure from ideal structure in the ground. The accuracy of readings is, of course, less when the long-range dial is used.

GENERAL DISCUSSION

The equipment used in this work comprises a sledge-hammer, a seismometer, two boxes of electronic equipment, two 6 volt storage batteries, short interconnecting cables, a 250 meter reel of twin cable, a test meter, spares for the electronic circuits, a steel measuring tape, pick, and spade. It is easily transportable in a half-ton panel van. Two men are required for field work, one to operate the equipment and one to hammer. The operation of the equipment is simple and does not require a trained physicist or engineer. Electronic faults are infrequent, and it is probably best to bring the equipment back to the base laboratory for

electronic repairs. The time measuring circuits require a monthly or two-monthly recalibration in the laboratory.

The field tests have shown that about four long traverses (maximum range 250 meters, depth explored to about 150 feet) or six short traverses (maximum range 80 meters, depth explored to about 50 feet) can be made in a day. Wind of velocity greater than 10 mph and any considerable fall of rain will delay the work. The greatest depth found in the experimental field work was 154 feet to solid rock at Bronkhorstspruit. This depth was not subject to independent check. The greatest depth calculated and verified against a borehole was 77 feet at Kromellenboog.

Interpretation of the travel-time curves presents the principal problem; where there is considerable departure in the actual structure from any simple model, it may be difficult to decide what large-scale structure underlies the random scatter produced by inhomogeneities. It has, however, been possible to make a fairly reliable interpretation of all but one of the 24 traverses at the two field sites. Depths calculated at Kromellenboog agree satisfactorily with borehole data. An estimate of the precision of depth determination from a typical traverse at Kromellenboog indicates that depths are determined to about ± 15 percent. The contention that such variation is a measure of the actual structural variation and not of instrumental error is supported by the high accuracy of repetition of travel times for a traverse at Bronkhorstspruit. Other traverses at Bronkhorstspruit give depth determinations to various seismic horizons, but these depths are not subject to independent check.

During the early stages of the experimental work, attempts were made to work with reflections. These attempts were unsuccessful for three reasons.

(a) At short ranges, reflections of the *P* or *S* wave are, in the nature of short-range seismology, coincident in time with the surface (Rayleigh) waves. A small reflected wave must therefore be distinguished from a large surface wave.

(b) In conventional seismic reflection work, the identification of reflections is facilitated by means of an array of 12 or more seismometers. The seismometers must be spaced at intervals of the order of half a wavelength, which is a large fraction of the traverse length in this short-range work. It is therefore impracticable to use multiple seismometer arrays.

(c) When one is trying to pick out a new arrival superposed on a large continuous wave, as distinct from the first arrival used in refraction work, the conventional method has a great advantage in that a permanent photographic record is available for inspection, as against a transient image on a cathode-ray tube screen.

The first two are inherent in the nature of short-range seismology, the third in the nature of the instrument.

Another question which was investigated during the development project was that of source of seismic energy, and its coupling to the ground. The simple

hammer has been retained instead of any form of explosive source, or large mechanical hammer, because of its convenience, portability, and speed of working. A variety of targets has been tried, in an effort to improve the coupling to the soil, including a large pyramidal impact stake modified from the form suggested by Jakosky (Jakosky, 1950, p. 856). On the soils so far tested, this impact stake has invariably given inferior results to the direct hammer blow on the surface. It has been found, in general, that the seismic energy is greatest when the hammer bounces least. This would be expected from considerations of conservation of energy. On hard surfaces the direct hammer blow is best. On very loose sandy surfaces it has been found advantageous to place an iron plate $8\times8\times\frac{1}{2}$ inches on the ground and hit the plate. It is possible that the impact stake would be of assistance in very soft marshy ground.

It is interesting to compare the instrument here described with the conventional seismic refraction equipment for work at these very short ranges. The conventional method has the advantage of far greater seismic energy from the explosive source. This gives it a decisive advantage except at these very short ranges. Even at the very short ranges, the high energy level of the seismic disturbance means that the background seismic noise is negligible even in considerable winds, so that operations are less likely to be delayed by weather. A further advantage of the conventional method lies in the existence of a permanent photographic seismogram which can be studied at leisure.

The instrument here described can claim the following advantages:

(1) Speed of working. It should be remembered that an equally detailed travel-time curve to those shown would require the use of some 20 or 30 seismometers, if done from a single shot by the conventional method.

(2) Low cost, both capital and running. The equipment is inexpensive and requires only two men, one unskilled, for operation.

(3) No photographic processing is required. Evenings can be devoted entirely to plotting curves and computing results.

(4) The operator has the travel time for each point as the traverse proceeds. He can at once detect any change in the curve, and ask for repetition of a point or the insertion of extra points.

(5) The operator adjusts the amplifier gain at each range and so can see the waveform and identify a phase rather than a mere "first break."

(6) The cathode-ray tube cannot be harmed by accidental overload, whereas galvanometers may be broken. This is a real advantage when ranges vary in the ratio of 1/100.

(7) No explosives are used. This eliminates all the troublesome problems of transportation and storage of explosives.

(8) The electronic method of timing is much superior for travel times of the order 10 to 80 milliseconds encountered in this short-range work. The conventional type of recorder would require a paper speed of about 20 inches per second.

(9) Portability. The instrument can be carried to sites which would be quite inaccessible to a standard seismic recording van. The portability could be improved in any future model. The major problem here is the weight of lead batteries.

It would appear that the new instrument provides notable advantages at short ranges. Confirmation of this claim must await more extensive field trials, which will shortly be undertaken with the prototype instrument by the Geological Survey of the Union of South Africa.

Various practical applications of the instrument will emerge in the course of its use. The following applications are suggested as possible:

Investigation of dam sites.
Location of ancient river beds.
Investigation of country-rock round boreholes, using a seismometer down the hole.
Practical use of *S* phases using a horizontal seismometer.
Determination of depths of weathered zones, for water supply purposes.
Location of faults, crush-zones, dykes, step-structures (possibly using fan-shooting).
Low-velocity-layer correction work for reflection seismic purposes.

The last-named is thought to be an important possibility.

ACKNOWLEDGMENTS

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SEISMIC EXPLORATION OF THE DENVER-JULESBURG BASIN*

B. F. RUMMERFIELD†

ABSTRACT

Recent developments in northeastern Colorado and southwestern Nebraska have resulted in a marked increase in seismic activity within the Denver-Julesburg Basin.

The low relief of many of the subsurface structures, coupled with the extraneous effects of weathered zone, elevation changes, surface deposits, and velocity variation taxes the resolving power of the seismic method and the interpretative ability of the geophysicist.

INTRODUCTION

The Denver-Julesburg Basin has proven to be very attractive, from an exploration viewpoint, for both the major oil companies and the small independents. An indication of the recent increase in interest is shown by the comparison of twelve seismic crew months work done in the Basin for 1948 to an estimated four hundred and twenty-five crew months for 1951.

The ability to assemble large blocks of fairly inexpensive acreage, coupled with the low exploration cost, has contributed appreciably to the present activity. The cost of seismic work will vary from $1.00 to $2.00 per acre depending upon the amount of detail work necessary and the disposition of the acreage. This cost is considerably lower than that encountered in other regions of the Rocky Mountain province. Deep hole tests can be drilled in a minimum of time as the thick sections of Cretaceous shales lend themselves very readily to rapid rates of penetration. Another main consideration is the favorable discovery rate of 23 percent for the Denver-Julesburg Basin in 1950 as compared to 11 percent discovery rate for the same period of time in the rest of the United States. (Refer to Fig. 1.)

To date a major portion of the production has been found in the northeastern portion of the Basin. It is in this area that the geophysical exploration has been concentrated. It is reasonable to assume that the area of oil production will be enlarged as the exploration activity becomes more active in other parts of the Basin. The present "fairway" of producing wells will probably extend to the southwest and northeast where similar geological and reservoir conditions may be expected. (See Fig. 2, Regional Map and Fig. 3, Tectonic Map.)

The area trending north-south and immediately in front of the Rocky Mountains also offers interesting possibilities. The presence of the Boulder, Ft. Collins, Wellington, and other structures in the north part of this trend and the Florence

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Field in the south argue that similar structures and production may be found in the intervening regions.

One other possibility to be considered for the Basin is the testing of the deeper Jurassic and Pennsylvanian beds in all wildcats, whenever possible. It has been the history of practically all oil basins that shallow production is first discovered and, following a considerable lag of time, that deeper production is later found. In many cases the deeper production has proven to be the more prolific and proceeding from the same anomalies which have shallow production.

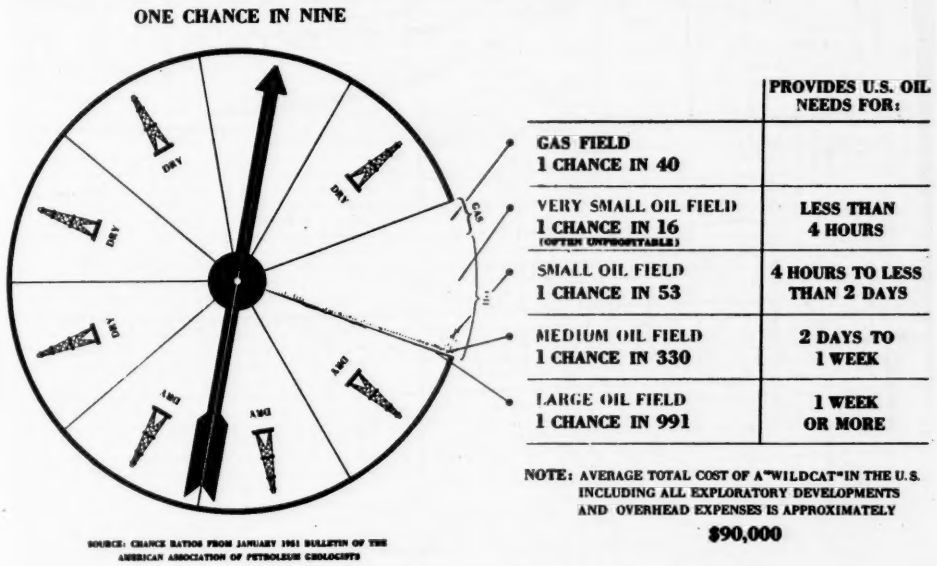

FIG. 1. Risk in hunting for oil.
(Courtesy of the API)

A greater part of the drilling, leasing, and exploration activity has been concentrated in northeastern Colorado and southwestern Nebraska. It is these areas to which a majority of this discussion refers.

FIELD PROCEDURE

The operation of the average seismic crew in the Denver-Julesburg Basin is a standard operation with the possible exception that allowances should be made, both in equipment design and personnel, for the rather severe weather conditions encountered during the winter months. Considerably more coverage can be obtained during the summer and fall months. It is relatively easy to transport truck-mounted equipment, although some local areas are encountered where surface sand conditions cause difficulties. The region is sectionized, and both land control and elevations are readily established from existing bench marks.

The obtaining of permits is no major problem—normally verbal permits suffice. No fee is being paid for permits in the area at present, but payments are

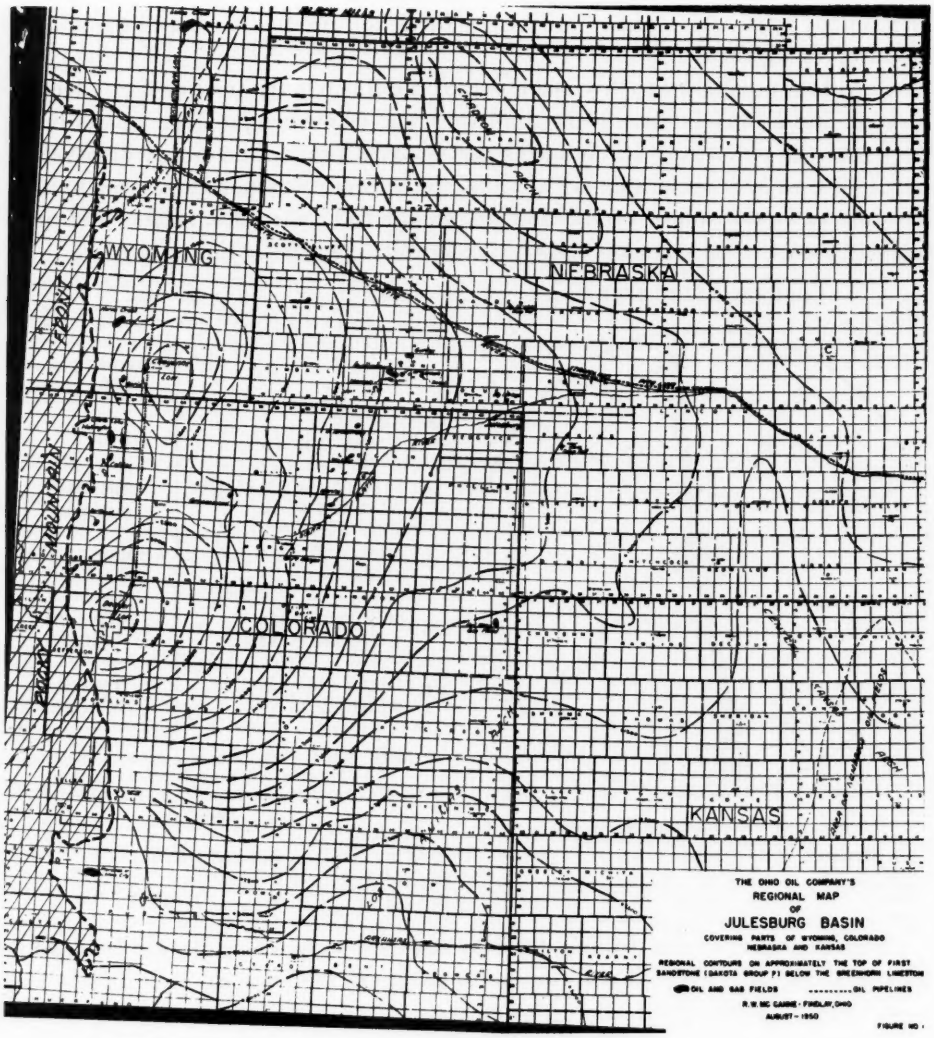

FIG. 2. Regional map, Denver-Julesburg basin.
(Courtesv of the Ohio Oil Co .)

made in the event of damaged crops, roads, or surface rights. During the past year it has been very noticeable that the attitude of the farmers is gradually becoming less and less cooperative. Field trips reveal that some seismic crews are still very lax in their field procedures and their public relations with farmers and townspeople. It would behoove all operators in this area to check their crews for these weak points in order to avoid the additional cost and difficulties encountered in regions where farmers have become "tough" as the result of poor treatment.

The area has a natural division into two portions from the viewpoint of surface geological beds: First, the part of northeastern Colorado in which the upper Cretaceous beds are exposed (Pierre Shale and Fox Hills Sandstone) and, secondly, that portion of southwestern Nebraska in which the surface beds consist of Tertiary (Ogallala and Arickaree) deposits and Quaternary alluvium and windblown sands. In the areas of Upper Cretaceous outcrops, the drilling of seismic shot holes is a relatively simple procedure, and good records can be expected by shooting at depths ranging from 60 to 100 feet. The regions covered by the Tertiary and Quaternary beds cause considerable difficulty in the drilling of shot holes because of the thick beds of sand and gravel present. In such areas, it is sometimes necessary to drill shot holes as deep as four to five hundred feet.

Over-all, the record quality obtained in the Julesburg Basin is sufficiently good to allow a reconnaissance type of correlation seismic control. (See Figure 4.) In such cases shot holes are placed either on section corners or on half lines at approximately one mile intervals, and in some areas shot holes are also located near the centers of the sections. This control is kept flexible enough to allow considerable latitude in locating of shot points, with the idea in mind of obtaining maximum coverage in a minimum of time. After the preliminary reconnaissance control is established, any areas of interest within the survey are

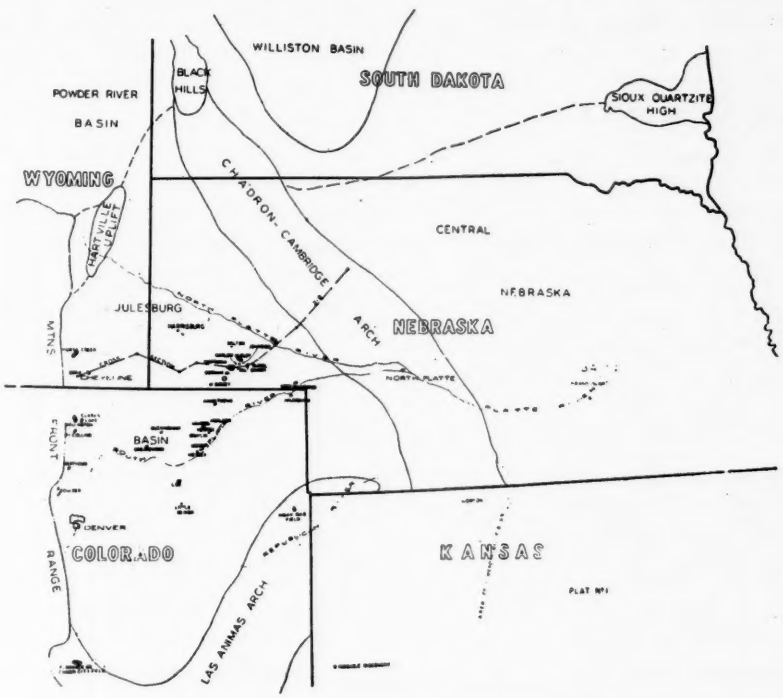

FIG. 3. Tectonic map, Denver-Julesburg basin.
(Courtesy of the Ohio Oil Co.)

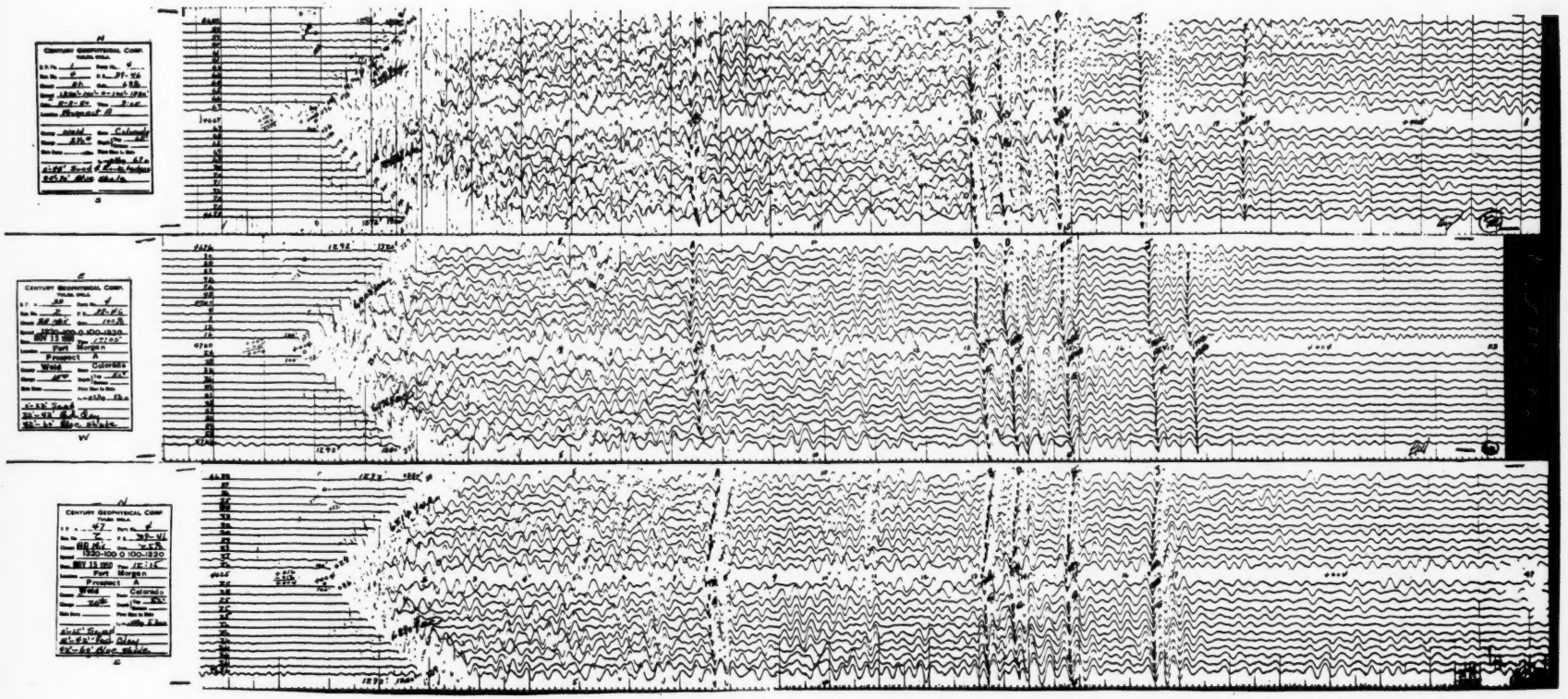

FIG. 4. Specimen seismic records: Reflection "A" is probable Hygiene sand, "B" is probable Niobrara, "D" is probable Dakota, "F" is probable Lakota, and "J" is probable Morrison.

detailed by lines of continuous seismic traverse, preferably using closed loops. If an additional check is desired, deep hole velocity surveys are shot to make certain that near-surface velocity variations are not the causes of the anomalous feature being investigated.

The spread of geophone arrangement should be designed to obtain maximum record quality. The use of short geophone intervals and shot point cluster of geophones is advantageous in the obtaining of high quality records to be used for correlation interpretation. The group of geophones placed equidistantly around the shot point also allows a comparison between the near geophones which are used to obtain the reflection times. In this way, any trace that appears erratic can be ignored in the timing of the reflections. Normal "split spreads" or "end-on spreads" are satisfactory for the continuous program, with preference being given to "split spreads" because of the smaller number of shots necessary from each shot hole.

INTERPRETATION

Reflections are usually obtained from the Niobrara and the Dakota members of the Cretaceous period and from the Morrison sandstone of Jurassic age. Less persistent reflectors are the Hygiene Sand, Ft. Hayes limestone, Greenhorn limestone, Lakota formations and Pennsylvanian horizons. Normally the most outstanding reflection is obtained from the Niobrara, although other reflecting horizons may predominate in local areas. The "character" of this reflection is generally recognizable. This "character," in conjunction with other less noticeable reflection characteristics and reflection groupings, allows a creditable correlation of records over broad areas.

In addition to the structural maps prepared, good practice prompts the construction of as many reliable isopach maps as possible. However, experience has shown frequent lack of agreement between structural trends and isopach maps in the Julesburg Basin. A study of well logs, such as the sections prepared by the Rocky Mountain Association of Geologists (see Figs. 5 and 6), clearly indicates that often the depositional cycles within the Cretaceous period were erratic; local thickening and thinning of deposits may occur that have no relationship to structure.

In the areas of thick Tertiary and Quaternary mantles, the obtaining of satisfactory seismic records at times becomes a serious problem. Even when usable records are recorded, the weathering and elevation corrections offer many complications. If possible, it is advisable to penetrate these surface deposits so that a direct time measurement can be obtained by the uphole phone, but in some areas this is not economically feasible as the Tertiary sands and gravels may exceed 1,000 feet in thickness. In these regions it is advisable to shoot at as near a constant shot elevation as possible.

One somewhat unique approach which has been used in such cases is to drill a widely spaced symmetrical pattern of deep holes penetrating the Tertiary and

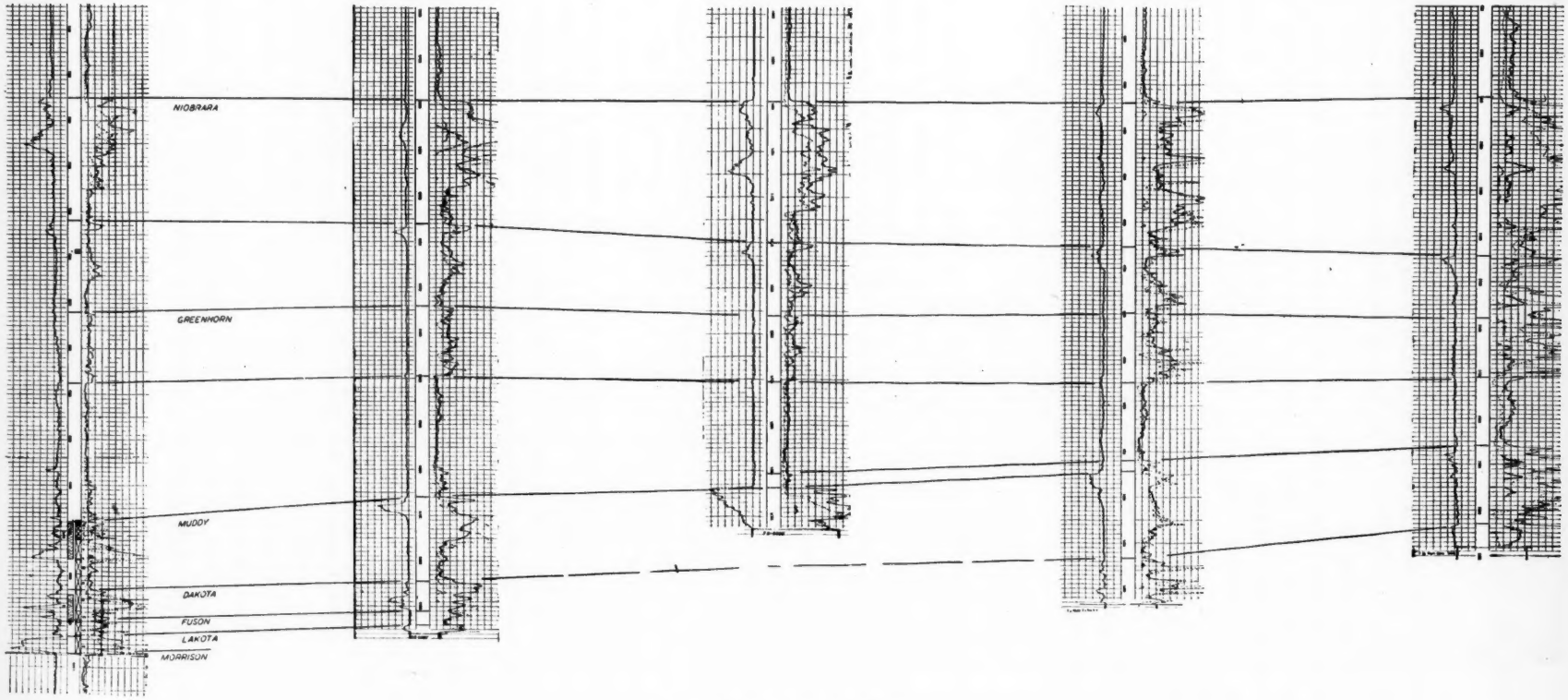

FIG. 5. Electric log correlations.

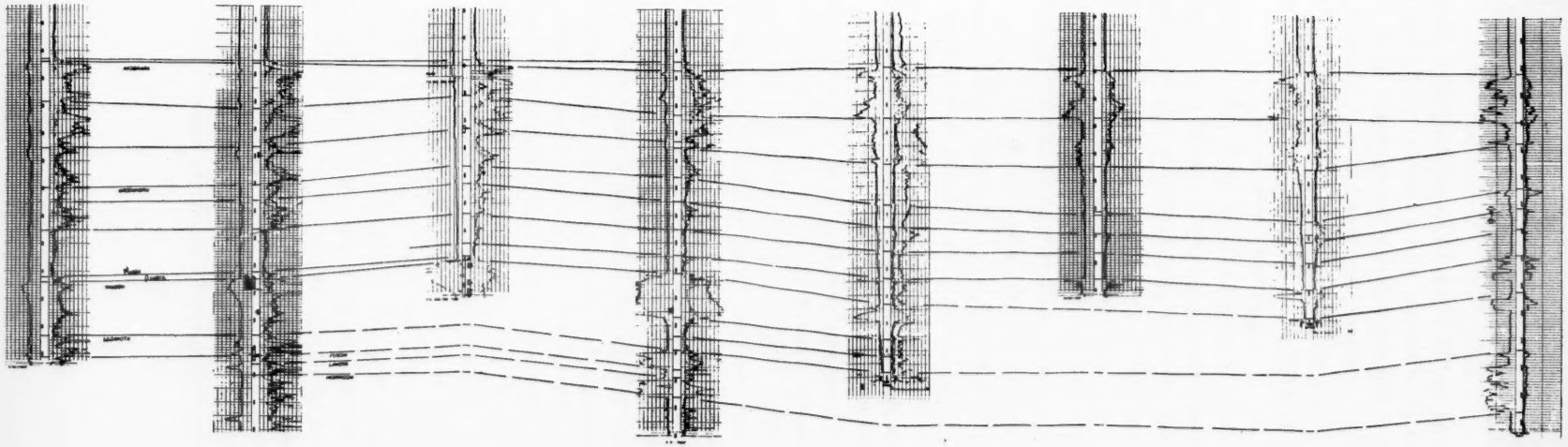

FIG. 6. Electric log correlations.

Quaternary surface beds in the block to be investigated. These deep holes are shot for uphole velocity information, and a study is then made of the data to ascertain whether or not a uniform velocity change takes place. If an areal change in velocities is present, it is sometimes possible to establish a velocity gradient for the area. An iso-velocity grid overlay can then be constructed, and a variable elevation velocity can be applied to the corrections for shot points that did not penetrate surface Tertiary or Quaternary beds.

Special attention should be paid to refraction breaks throughout the area, not only to evaluate any erratic step-outs of reflections, but also to recognize immediately any sudden change in near-surface velocity. Other weathering corrections such as Blondeau, summation, and multi-layer corrections may be applied if necessary.

Correcting time data to the elevation of the shot, rather than using a constant elevation reference plane, will give an indication of the effect, if any, of changes in surface elevations or near-surface velocities.

An interesting sidelight relating to this general subject is that in one area where it was possible to drill through the Tertiary beds, a consistent red clay bed was encountered immediately above a blue shale (Pierre(?)). The red marker bed was persistent enough to suggest that the blue shale top was a stratigraphic surface, and not an erosional surface as originally thought. A map of the elevations of the blue shale tops was prepared, and, when contoured, the structure generally conformed to the structural maps constructed on the deeper reflecting horizon. A similar study can be undertaken to determine the cause or effect that sometimes exists between surface topography and sub-surface structure.

The erratic surface deposits cause a great deal of difficulty in the calculating of satisfactory weathering corrections. It is this factor which is believed to result in an inherent, or "built-in," limit of error in various areas. Many of the subsurface structures found within the Julesburg Basin are of relatively low magnitude, with closure ranging from 25 to 100 feet. This low relief accentuates the critical nature of the near-surface corrections, as the amount of closure of some of the anomalies lies almost within the limit of error of the seismic method.

A "mathematical trick" that sometimes facilitates the contouring of seismic data in regions of low sub-surface relief is to divide the area into a network of triangles, using adjacent shot-points as the apices of small, nearly-equilateral triangles. The corrected reflection data of the apices of the small triangle are averaged, and the average value is plotted in the center of the triangle. The new set of data smooths out individual high or low values, and often gives a more "natural" or geological appearing map.

The effect of velocity gradients is little understood in the Denver-Julesburg Basin at present chiefly due to the lack of velocity control. However, it is believed that this factor is a sizeable one for this province and may, in many cases, contribute to the rather "abnormal" appearing seismic maps that often are ob-

tained. Considerable attention should be given to this problem as more velocity control becomes available.

There are many interpretational and computational approaches other than those mentioned above that may be used in addition to standard procedures. It is advantageous to use as many of these methods as practical so that the results can then be compared to maps constructed by using routine computations.

CONCLUSIONS

Discoveries to date, plus the size of the area to be investigated, make certain that oil exploration will probably continue in the Denver-Julesburg Basin at its present level for several years.

Generally fair-to-good seismic results can be obtained over a majority of the Basin. However, considerable care should be taken in evaluating anomalies to make certain that such features are the results of sub-surface structural conditions and are not merely a measurement of variations in weathered zones, topography, near-surface beds, or velocities. The use of additional interpretational and computational approaches is valuable in segregating areas of disagreement in data; such areas warrant further investigation.

It should be pointed out that regardless of the above discussed seismic limitations and problems it is believed that a majority, if not all, of the present oil discoveries in the Denver-Julesburg Basin have been located and drilled on seismic anomalies.

THREE DIMENSIONAL INTERPRETATION OF GRAVITATIONAL ANOMALIES*

FRASER S. GRANT†

ABSTRACT

A method is developed for determining the approximate size and shape of the three-dimensional mass distribution that is required to produce a given gravitational field. The first few reduced multipole moments of the distribution are calculated from the derivatives of the surface field, and the approximative structure is determined from the values of these moments and a knowledge of the density contrast between the body and its surroundings. A system of classification of problems by symmetry is introduced and its practical usage discussed. A relaxation method is described which may be used to adjust the initial solution systematically to give agreement over the whole field. A descriptive discussion is appended.

PART I

1. STATEMENT OF THE PROBLEM

The resolving power of modern gravity meters is such that the elaborate reductions for latitude, free air, Bouguer, regional, and terrain effects may be applied with some confidence to data recorded within a limited area. Frequently, the map of the residual gravity reveals regular patterns in the distribution of the residues over the datum plane, which may manifest themselves in the closure of certain sequences of contours. Individually, such patterns are termed "anomalies" and are presumed to have their origin in excesses and defects of density within the materials of the shallow crust. It is understood that the "geophysical interpretation of gravitational anomalies" has as its objective the estimation of the magnitudes and distributions of the masses that cause them and the determination of their relation to the geology of the area involved.

Physicists are inclined, for the sake of mathematical clarity, to idealize the geological conditions somewhat, and to picture the density variations as being bounded, i.e., contained within physically closed envelopes which rest within an otherwise perfectly homogeneous medium bounded by a horizontal plane surface of infinite extent, as is suggested by Figure 1. The methods of interpretation proceed from the fact that each such bounded distribution of anomalous density changes the total field of force at the surface by the attraction due to a body having the same size, shape, and position, and having a density which is the difference between that of the anomalous matter and that of the surrounding material. Such a description may have conspicuous deficiencies, but it serves well enough to give approximate representations of many types of mineral deposits which have very local occurrence.

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Therefore, the problem is: given, at a network of points over a horizontal plane, the normal component g of a field derivable from a potential, to find the position, size, and shape of the mass distribution producing the field. For verbal convenience, g designates henceforward the residual gravity anomaly at a point, after the application of all reductions required by the survey.

The usual line of attack has been to guess at a suitable mass distribution and then to calculate its gravitational field and to compare this with observations. The trial distribution may then be adjusted by a sequence of "cut-and-try" improvements aimed at obtaining a better fit. The initial guess frequently is facilitated by prior knowledge of the geology of the area and by the use of "type curves," i.e., theoretically computed profiles of the gravitational fields of artificial bodies such as rectangular prisms, vertical steps, and the like. Although a very great deal of ingenuity and labor has been devoted to the accumulation of these curves and to the construction of diagrams and charts to aid in the computations (e.g., Jung, 1927; Numerov, 1927; Lancaster-Jones, 1929; Hubbert, 1948; and others), the application of type curves is restricted to the special class of problems which may fairly be regarded as "two-dimensional," i.e., those involving structures which extend to infinity in one direction, lie parallel to the surface of the ground, and whose cross-sections are unchanging along their infinite length. Moreover, the continued amassment of type curves presages the unpleasant consequence of multiplying the chances for casual ambiguity, viz., the appearance of indistinguishably similar curves in several different files at once. Thus they offer little assistance in the solution of problems of the "three-dimensional" genus. In comparison, strangely little attention has been given to the problem of calculating mass distributions directly from the maps of anomalies (e.g., Jung, 1937); and, within the writer's knowledge, there is no general method that is equipped to deal with three-dimensional* structures, with the single exception of the sphere. In this paper a method is developed for this purpose, and in a following paper it will be applied to certain examples. The gravitational problem is dealt with throughout, but the general procedure could be used in other branches of potential theory.

2. INTRODUCTION

The problem begins at this point: it is assumed that a gravity survey has been taken over a given area, that all reductions have been made, that the station-spacing is sufficiently fine to allow careful contouring of the results, and that an anomaly pattern appears amongst the residues. If more than one pattern appears, they must be distinctly resolved from one another. There are many excellent methods available for performing the reductions with care (e.g., Numerov, 1924; Lancaster-Jones, 1935; Hammer, 1939), and there is no intention here of inquiring into them. The purpose of this paper is to develop a method for deter-

* The term "three-dimensional" is intended to imply that the body is not greatly extended in any direction.

mining the size, shape and position of the three-dimensional mass distribution that reproduces an observed anomaly pattern.

Any closed distribution of mass can be replaced with a point mass, a triple of dipoles, a quintuple of quadrupoles and an infinite series of multipoles of higher orders all superposed at some given point in the body, without affecting its external field in any way. The separate contribution of each multipole to a measurement of the total field at an external point diminishes as the order of the multipole increases or until a zero coefficient is attained in the series. Now, if it is assumed that the body is spherical, only the first of an infinite series of terms is taken into account, and, while it is the largest term, it is not the only one that is recorded by the gravimeter. Taken by itself, it can be expected to yield a reasonably good estimate of a non-symmetrical deposit only if the latter is small and/or deeply buried, and, of course, no inferences can be drawn from it about the shape. It is important to realize that the limitation of this method lies principally in the mathematical oversimplification, rather than in any dubiety among the data. On the other hand it is possible to conform to the accuracy of virtually every practical problem by replacing any distribution of mass with all of its multipoles up to and including order three—that is, including octupoles; the total contribution from the remainder will in almost any conceivable case lie beneath the sensitivity of modern instruments, or beyond the accuracy of the reductions.

It is proposed to make this substitution, and to devise a means of calculating numerical values for these moments directly from the data. The shape and dimensions of the body may be calculated uniquely from the moments, if the density contrast between the orebody and its surroundings, or the law of variation of density within the orebody, is known. Through the remainder of Part I of this paper, it must be presumed that there is at our disposal a method for computing from the data the derivatives of the residual gravity field at a given point with sufficient accuracy for our purpose. A method that is particularly suitable to this object will be presented in a separate paper as Part II.

The application of mathematical theory to geological problems is given a somewhat more realistic basis in this work, by removing the necessity for assuming perfect homogeneity of the host rock.* Although the device by which this is achieved will be presented with Part II, its consequences apply throughout the entire work, and so it is simply stated *ab initio* that all formulae contained within this paper are derived under the assumption that random inhomogeneity is present in the country rock, and so they are in no way vitiated by it.

3. THEORY

The gravitational potential at an exterior point due to a continuous distribution of mass contained within a volume V is:

* "Statistical homogeneity" is required however, which means that inhomogeneities may be present to any degree, but they must be randomly distributed; i.e. the theory cannot take into account any systematic bias in the distribution of their effects.

$$U_p = G \int_V \frac{\rho(r_0) d\tau_0}{| R - r_0 |} \tag{1}$$

where $\rho(r_0)$ is the volume density and G the universal gravitational constant. The origin o may be located anywhere within V.

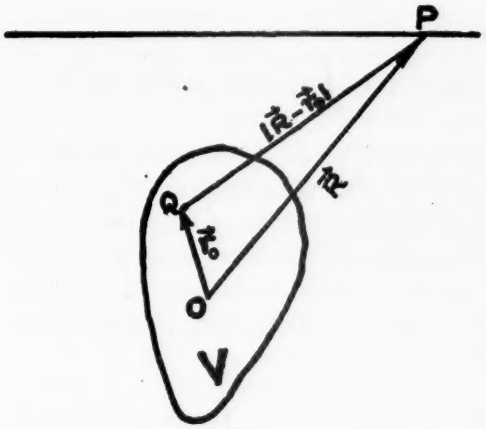


FIG. 1

Now

$$\frac{1}{| R - r_0 |} \equiv \frac{1}{\sqrt{R^2 + r_0^2 - 2Rr_0 \cos \gamma}} = \frac{1}{R} \sum_{l=0}^{\infty} \left(\frac{r_0}{R} \right)^l P_l(\cos \gamma), \qquad R > r_0,$$

where P_l is the Legendre polynomial of order l, so that

$$U_p = (G/R) \sum_{l=0}^{\infty} \int \rho(r_0)(r_0/R)^l P_l(\cos \gamma) d\tau_0. \tag{2}$$

The addition theorem of Legendre polynomials can be given the following formulation:

$$P_l(\cos \gamma) = 4\pi/(2l + 1) \sum_{m=-l}^{m=l} y_l{}^{m*}(\theta_0, \phi_0) y_l{}^m(\theta, \phi), \tag{3}$$

where (θ_0, ϕ_0) are the polar angles of $\vec{r}_0$, (θ, ϕ) are those of $\overrightarrow{R}$,

$$y_l{}^m(\theta, \phi) = \left[\frac{2l + 1}{4\pi} \cdot \frac{(l - |m|)!}{(l + |m|)!} \right]^{1/2} e^{im\phi} P_l{}^{|m|}(\cos \theta),$$

and where $P_l{}^{|m|}$ is the associated Legendre polynomial. Combining (2) and (3) gives:

$$U_p = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} \frac{4\pi G}{2l+1} \int_V \rho(r_0) r_0{}^l \cdot y_l{}^{m*}(\theta_0, \phi_0) d\tau_0 \cdot \frac{y_l{}^m(\theta, \phi)}{R^{l+1}}$$

$$\equiv \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} b_l{}^m y_l{}^m / R^{l+1}, \tag{4}$$

where

$$b_l{}^m = 4\pi G/(2l+1) \int_V \rho(r_0)(r_0)^l y_l m^*(\theta_0, \phi_0) d\tau_0.$$

These $b_l{}^m$ constitute, for a given l, the $2l+1$ possible "reduced 2^l-pole moments" of the structure. It is doubtful that they may be thought of as representing multipoles in any real physical sense, but their form and their behavior apparently justify this connotation in every other way. Since they do not receive explicit mention in any of the well known books on potential theory, this nomenclature must suffice. In most practical cases, ρ is considered to remain constant everywhere throughout V, so that

$$b_l{}^m = 4\pi G\rho/(2l+1) \int_V (r_0)^l y_l{}^{m*}(\theta_0, \phi_0) d\tau_0. \tag{5}$$

The series (4) and the coefficients (5) may be expressed in rectangular coordinates through the transformations:

$$R = \sqrt{x'^2 + y'^2 + z'^2}, \qquad \theta = \cos^{-2} z'_0/R, \qquad \phi = \tan^{-1} y'/x'. \tag{6}$$

and

$$r_0 = \sqrt{x'_0{}^2 + y'_0{}^2 + z'_0{}^2}, \quad \theta_0 = \cos^{-1} z'_0/r_0, \quad \phi_0 = \tan^{-1} y'_0/x'_0.$$

4. SYMMETRY CLASSIFICATION

The reduced multipole moments take their simplest algebraic forms when the axes are chosen in the following way: a) the origin of coordinates lies at the centre of gravity of V. (One need only consider the case of a uniform sphere as an example.) b) the z'-axis follows the line of greatest symmetry of V, and c) the x' and y' axes follow lines of lesser symmetry, if any. Such a frame of axes will be called the 'body axes.'

Clearly the description of V must be known in order to evaluate the coefficients (5), and in this connection it becomes desirable to introduce the concept of symmetry groups. Within the framework of this idea, every solid which might be found useful in geophysical interpretation is assigned, according to the symmetry it possesses, to one of four groups. The classification that is introduced here is somewhat arbitrary: it is based entirely upon the evanescence of certain of the reduced moments with respect to the body axes. However, it is found

that all solids belonging to a given group possess one or more elements of symmetry in common, and this is strongly suggestive that the common element or group of elements constitutes the basic definition of the group. If this is so, then there are such close analogies between these groups and some of the common crystal systems that the classification of the groups by symmetry, and the use of the nomenclature of crystallography is suggested immediately.

Groups are listed in order of their symmetry in the following table, in which column 2 gives the group symmetry. The notation is quite standard: C_n defines an axis of n-fold rotational symmetry, NC_n denotes that there are N such axes, $\overline{C}_n$ implies that the axis is normal to a plane of reflection, and mC_n, that the axis passes through a plane of reflection. Column 1 lists the crystal systems that are associated in each case with the symmetry operations of column 2; these have been adopted as names for the groups. Column 3 shows a catalog of the non-vanishing reduced moments from $l=0$ to $l=3$, and column 4, some of the member solids.

1 Name of group	2 Basic Symmetry	3 Non-vanishing Multipole Moments	4 Sample Solids
Cubic	$4C_3$	b_0^0	Cub Sphere
Tetragonal	$\overline{C}_4$	b_0^0, b_2^0	Circular cylinder Tetragonal block Ellipsoid of revolution
Orthorhombic	$3C_2$	b_0^0, b_2^0, $b_2^{\pm 2}$	Elliptical cylinder Rectangular block Ellipsoid
Monoclinic	$\overline{C}_2$, mC_2	b_0^0, b_2^0, $b_2^{\pm 2}$ b_3^0, $b_3^{\pm 2}$	Symmetric trapezoidal block Symmetrical wedge Rhombic block (Parallelopiped)

Few solids of any practical importance in geophysics are excluded from this scheme; yet it allows only four possible forms of expression for any gravitational field. The actual expressions for the moments of some of these examples are given in an Appendix.

5. THE OBSERVER'S FRAME OF REFERENCE

Geophysical field measurements are taken over the surface of the ground, which for practical purposes may be considered to be a horizontal plane. It is convenient to refer these observations to a frame of axes in which the z-axis is vertical: such a frame will be called a spatial frame. The spatial frame whose origin lies at the center of gravity of V we will call the "observer's frame of refer-

ence." Then the co-ordinates in the observer's frame of reference are related to those in the body frame through the usual transformation

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} l_1 & m_1 & n_1 \\ l_2 & m_2 & n_2 \\ l_3 & m_3 & n_3 \end{pmatrix} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}. \tag{7}$$

Six conditions of orthogonality are satisfied among the nine elements of the (l, m, n) matrix, so that the orientation of the body axes in the observer's frame of reference is described by three mutually independent parameters. If we choose for this purpose the Eulerian angles (Φ, Θ, Ψ) defined in their usual sense, the matrix elements will be

$$\begin{aligned} l_1 &= \cos\Psi \cos\Theta \cos\Phi - \sin\Psi \sin\Phi \\ l_2 &= -\sin\Psi \cos\Theta \cos\Phi - \cos\Psi \sin\Phi \\ l_3 &= \sin\Theta \cos\Phi \\ m_1 &= \cos\Psi \cos\Theta \sin\Phi + \sin\Psi \cos\Phi \\ m_2 &= -\sin\Psi \cos\Theta \sin\Phi + \cos\Psi \cos\Phi \\ m_3 &= \sin\Theta \sin\Phi \\ n_1 &= -\cos\Psi \sin\Theta \\ n_2 &= \sin\Psi \sin\Theta. \\ n_3 &= \cos\Theta. \end{aligned} \tag{8}$$

Through the successive application of the transformations (6) and (7) to the series (4), it is possible to express the gravitational potential of the distribution V in the co-ordinates of the observer, i.e.,

$$U_p(R, \theta, \phi) \rightarrow U_p(x', y', z') \rightarrow U_p(x, y, z_0) \tag{9}$$

where z_0 is the depth of the center of gravity of V below the ground (Fig. 2). In appendix I, the first few moments of a number of the structures listed in §4 as examples of the four symmetry groups have been calculated. It will be clear from these expressions that the reduced multipole moments are functions only of the parameters which define the shape of V, apart from the assumed (constant) density, and so must be invariant under any transformation of the axes. The body axes of V are not affected by the rotation; therefore, from the expression (9) and its derivatives, we are now required to determine three angles of orientation of V in the observer's frame of reference, as well as the dimensions of V.

6. CONVERGENCE

It has been pointed out by Kellogg (p. 144, problem 3) that if the series (4) is truncated at the nth term, that is, if we write

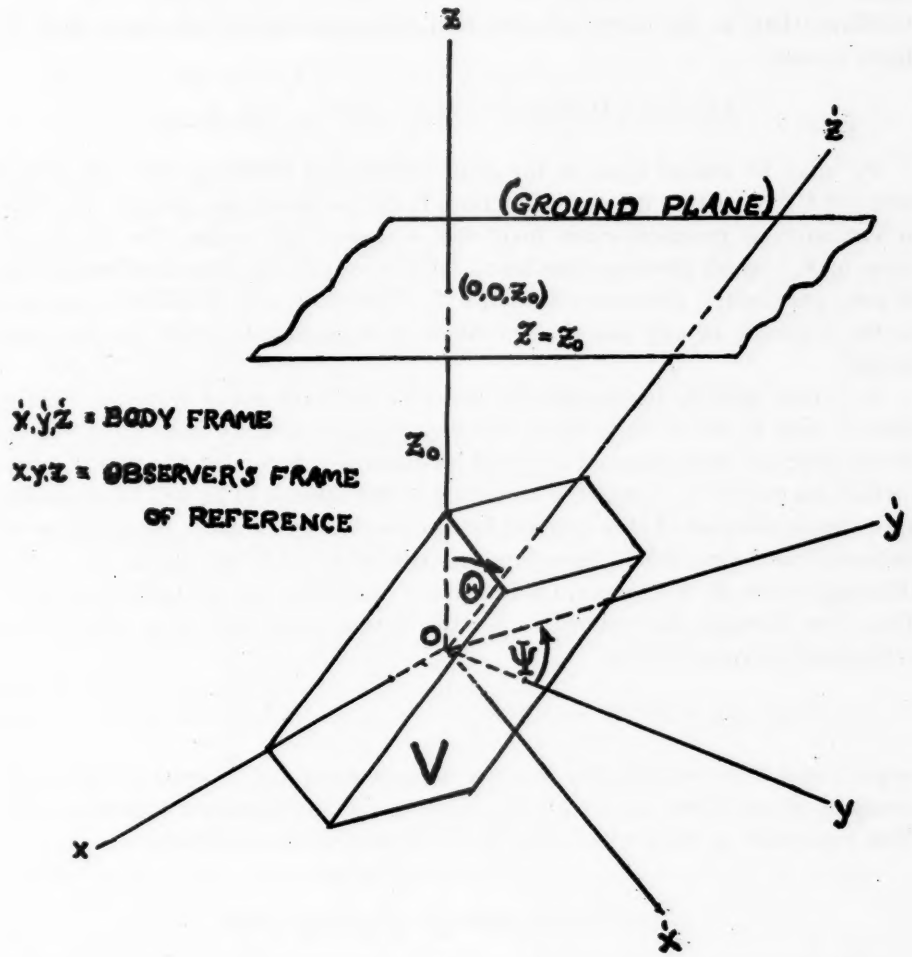


FIG. 2

$$U_p = \sum_{l=0}^{n} \sum_{m=-l}^{m=l} b_l{}^m y_l{}^m / R^{l+1} + R_n,$$

then the remainder R_n satisfies the inequality

$$| R_n | \leqq GM/b(a/b)^{n+1}(1 - a/b)^{-1},$$

where a is the radius of the sphere about the origin containing all of the mass M, and b is the radius of a larger concentric sphere to the exterior of which the point P is confined. If we write

$$\left.\frac{\partial U}{\partial z}\right|_{z=z_0} \equiv U_{z_0} = \sum_{l=0}^{n} \sum_{m=-l}^{m=l} b_l{}^m \frac{\partial}{\partial z}\left[\frac{y_l{}^m}{R^{l+1}}\right]_{z=z_0} + R_n',$$

it follows that, in the observer's frame of reference and for the same ratio of depth to size,

$$|R_n'| \leqq GM/b^2(a/b)^{n+1}(1 - a/b)^{-1} \qquad b \geqq z_0.$$

R_n' may be looked upon as the error inherent in assuming that the first n terms of U_{z_0} constitute the exact function. It can be shown in a general way that in virtually all practical cases involving non-extended bodies, the maximum value of R_n', which obtains when $b = z_0$, falls to roughly the threshold sensitivity of most gravimetric instruments when $n \leqq 3$. Therefore, it is possible to conform to the accuracy of any practical problem by replacing U_{z_0} with its first four terms.*

It is now possible to simplify the series (9) in three major respects. Firstly, since U and all of its derivatives can be computed directly from g, as will be shown later, all terms beyond $l = 3$ will be discarded. Secondly, the terms whose coefficients vanish by symmetry according to the scheme of §4 will be discarded also; the significance of this step will be discussed in §7. Finally, inasmuch as all moments can be made real, grouping the pairs of terms $b_l^m y_l^m$ and $b_l^{-m} y_l^{-m}$ into the single terms $B_l^m Y_l^m$, gets rid of imaginary quantities and normalizing factors. Thus, for example, the potential over the datum plane due to a solid having orthorhombic symmetry is

$$U_p(x, y) = B_0^0/R + (B_2^0/R^5) f(x, y, z_0) + (B_2^2/R^5) h(x, y, z_0) \qquad (10)$$

where f and h are polynomials that are homogeneous and of order 2, the coefficients of whose terms are simple functions of the trigonometric arguments (8). This expression is exact within the limits of practical measurement.

7. THE FORMAL BASIS OF INTERPRETATION

The series (9) is absolutely and uniformly convergent in the neighborhood of any point outside of V. This property is also shared by all derivatives of U (Kellogg, Ch. V), and so it follows that all derivatives may be formulated by differentiating expressions such as (10) term by term. The derivatives of U take particularly simple forms at the point $(0, 0, z_0)$, which lies on the ground directly above the center of gravity of V. If quantities which have been formulated at this particular point are denoted by a superscript ^{0}, then, with the aid of (8), the following algebraic identities may be established:

* Bearing in mind that the representation of the gravitational potential of V by a series is valid only if $a \leqq z_0$. If it is suspected (e.g. from elongated contour lines) that the body is not largely contained within a sphere about its mass center tangent to the ground, then other methods should be used (e.g. Jung, 1937).

Case I. If V has Monoclinic Symmetry

$$B_0^0 = -1/6(20z_0^2U_z^0 + 10z_0^3U_{zz}^0 + z_0^4U_{zzz}^0)$$

$$B_2^0 = 1/4z_0^3 \tan\Theta(5z_0U_x^0 + z_0^2U_{xz}^0) - 1/4z_0^3(4U^0 + 6z_0U_z^0 + z_0^2U_{zz}^0)$$

$$\tan 2\Theta \doteq \frac{20z_0U_x^0 + 4z_0^2U_{xz}^0}{3i_y + 28z_0U_z^0 + 17z_0^2U_{zz}^0 + 2z_0^3U_{zzz}^0}$$

$$\tan 2\Psi = \frac{5z_0^4U_y^0 + z_0^5U_{zy}^0}{z_0^4 \sec\Theta(5U_x^0 + z_0U_{xz}^0) - 6B_2^0 \sin\Theta}.$$

$$B_2^2 = -\frac{5z_0^4U_y^0 + z_0^5U_{zy}^0}{2 \sin 2\Psi \sin\Theta},$$

$$B_3^0 = (5\sin^2\Theta - 3)^{-1}\left[\frac{z_0^4 \operatorname{cosec}\Theta}{120}(9z_0^3U_{zzz}^0 - 30z_0^2U_{zz}^0 + 20z_0^3U_{xxz}^0) - B_3^2 \cos 2\Psi \cos^2\Theta\right], \quad (11)$$

$$B_3^2 = (8z_0^5U_y^0 + 2z_0^6U_z^0{}_y)/\sin 2\Psi \sin 2\Theta, \quad \text{where} \quad i_y = -\int_{-\infty}^{\infty} U_{z_0}\Big]_{x=0} dy,$$

and the following equations for determining z_0:

$$\begin{aligned} &12U^0 + 28z_0U_z^0 + 11z_0^2U_{zz}^2 + z_0^3U_{zzz}^0 = 0, \\ &20U_x^0 + 10z_0U_{xz}^0 + z_0^2U_{zzz}^0 = 0, \\ &20U_y^0 + 10z_0U_{zy}^0 + z_0^2U_{zzy}^0 = 0. \end{aligned} \quad (12)$$

Case II. If V has Orthorhombic Symmetry

$$B_0^0 = -2z_0^2U_z^0 - \frac{z_0^2}{2}U_{zz}^0,$$

$$\tan 2\Theta = -\frac{z_0^2U_{xz}^0}{3z_0^2U_{zz}^0 + 12z_0U_z^0 + 3i_y},$$

$$B_2^0 = \frac{z_0^4}{48}[2z_0(U_{xz}^0 - 2U_{yy}^0) + 2U_z^0 - 3 \operatorname{cosec} 2\Theta z_0U_{xz}^0], \quad (13)$$

$$\tan 2\Psi = \frac{2z_0U_{zy}^0}{\sin\Theta[2z_0(U_{xz}^0 - 2U_{yy}^0) + 2U_z^0 + z_0 \operatorname{cosec} 2\Theta U_{xz}^0]},$$

$$B_2^2 = \frac{z_0^5U_{zy}^0}{8 \sin\Theta \sin 2\Psi},$$

and the following equations for z_0:

$$
\begin{aligned}
&z_0^2(3U_{xx}^0 + U_{yy}^0) - 10z_0U_z^0 - 3i_x = 0, && z_0U_{xz}^0 + 4U_x^0 = 0,\\
&z_0^2(3U_{yy}^0 + U_{xx}^0) - 10z_0U_z^0 - 3i_y = 0, && z_0U_{zy}^0 + 4U_y^0 = 0,\\
&z_0^2U_{zz}^0 + 5z_0U_z^0 + 3U^0 = 0, && z_0U_{zzx}^0 + 5U_{zx}^0 = 0,\\
&z_0^2U_{zzz}^0 + 7z_0U_{zz}^0 + 8U_z^0 = 0, && z_0U_{zzy}^0 + 5U_{zy}^0 = 0,
\end{aligned}
\tag{14}
$$

where

$$
i_x = -\int_{-\infty}^{\infty} Uz_0\Big]_{y=0} dx.
$$

Case III. If V has Tetragonal Symmetry

$$
\begin{aligned}
B_0^0 &= -2z_0^2U_z - \frac{z_0^3}{2}U_{zz}^0\\
\tan\Phi &= \frac{U_{xy}^0}{U_{xx}^0} = \frac{U_y^0}{U_x^0} = \frac{U_{zzy}^0}{U_{zzx}^0}\\
\tan\Theta &= \frac{4\cos\Phi(U_{zz}^0 + 2U_{yy}^0)}{\cos 2\Phi U_{xx}^0}\\
B_2^0 &= z_0^4(2U_z^0 + z_0U_{zz}^0)/6(3\cos^2\Theta - 1)
\end{aligned}
\tag{15}
$$

and the same equations for determining z_0 as in case II.

The case of cubic symmetry is trivial.

It will be noticed that algebraic solutions for the monoclinic and orthorhombic symmetry groups are possible only if the observer's frame of reference is chosen so that $\Phi = 0$. The direction of one of the principal axes of any member of either group should be easy to gauge, to a first approximation, from the shape of the contours of its gravitational field over a plane. If it is not, then it must be assumed that the asymmetry of the body is small, and it should be dealt with through one of the higher groups.

The application of these formulae to the geophysical problem lies in relating U_{z_0} to g. The specific form of this relationship cannot be presented until Part II, but for the present purpose it is introduced quite inexplicitly here as constituting *the definition of the potential U*.

The practical use of the formulae will require some discretion. In some cases, geological formations may suggest a certain symmetry, although the completeness and the reliability of the data should be kept in mind when making a selection. In the absence of mandatory geological information, the degree of accuracy and detail of the surface data may dictate the choice of symmetry; for, among the more highly symmetrical groups, the calculations are more simple and the cross-checks more numerous, but the physical description is probably less real. In the rare case where the quality of the data is exceptionally good (as indicated by the agreement among the different calculations for z_0, for example), direct ap-

peal may be made to the monoclinic formulae to indicate which of the moments are dominant and which if any may be suppressed, and so to suggest by themselves the general form of the body. More frequently, however, the selection of a given symmetry class does not necessarily imply that there is any reason for believing that the structure possesses approximately such a symmetry. Rather, it means only that it is sufficient to approximate the actual body to a rectangular block, let us say, rather than to more complicated structures. The rapid convergence of the series for the potential is relied upon to mitigate the error.

In order to calculate structural details from the values of moments, it ultimately becomes necessary, of course, to choose a specific model. But this commitment comes at the very end of the numerical work, not the beginning; and then to exchange one model for another (from the same group) is very easy. This system seems to offer a wider flexibility than is found among those direct or indirect methods which require initial hypotheses concerning the specific shape of the body; for these hypotheses may be refined by calculations, but they cannot be changed in any fundamental way. It might seem surprising that the interpretation of surface data by this means is apparently unique. It must be remembered, however, that the mineral body has been replaced with a point mass and a superposition of three dipoles, five quadrupoles and seven octupoles, and since each of these taken separately may be determined unambiguously from surface data, it follows that their superposition should be determined uniquely also.

Quite a different point of view may be taken when the depth to a known point in the body is given or has been calculated by an independent method (e.g., Evjen, 1936; Bateman, 1946; Bullard and Cooper, 1948), for with this additional information no other assumption need be made for an unique interpretation. This is, in a sense, the converse of the previous problem, since it enables us to determine the approximate shapes of bodies, and may be applied to particular advantage to structures such as domes, ridges, troughs, and basins. Since these structures are quite generally flat-lying, it will not be far wrong to assume that $\Theta = \Psi = 0$. Then it can be shown that

$$
\begin{aligned}
B_0^0 &= 3zU^0 + 3z^2U_z^2 + \tfrac{1}{2}z^3U_{zz}^0. \\
B_1^0 &= -3z^2U^0 - 5z^3U_z^0 - z^4U_{zz}^0. \\
B_1^1 &= z^3 \sec \Phi(3U_x^0 - zU_{zz}^0) = z \operatorname{cosec} \Phi(3U_y^0 - zU_{zy}^0) \\
B_2^0 &= \tfrac{1}{2}z^3U^0 + z^4U_z^0 + \tfrac{1}{4}z^5U_{zz}^0. \qquad (16) \\
B_2^1 &= -z^4 \sec \Phi(3U_x^0 - zU_{zz}^0) = \text{etc.} \\
B_2^2 &= z^3 \sec 2\Phi(3U^0 + \tfrac{1}{4}z^2U_{zz}^0 + \tfrac{1}{2}z^2U_{xx}^0) = \text{etc.} \\
\tan \Phi &= U_y^0/U_x^0 = U_{zy}^0/U_{zz}^0.
\end{aligned}
$$

Some examples of models that are suitable for this type of problem are portions of spheres, ellipsoids, etc., and pieces of straight or curved cylinders, wedges, etc.

8. LOCATING THE POSITION OF THE CENTER OF GRAVITY

Each of the quantities to be used in the formulae (11)–(16) is to be evaluated at only one particular point in the field: viz., that point in the datum (ground) plane which lies directly above the center of gravity of the approximating structure V. At the beginning, therefore, a method is required for finding this point with reasonably good precision. The formal solution of this problem has been given by Kogbetliantz (1944), and his result is merely quoted here: the coördinates $\bar{x}$ and $\bar{y}$ of the center of gravity of a body V are given, in an arbitrarily chosen spatial frame, by the relations

$$\begin{aligned} \bar{x}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U_z(x, y)dxdy &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} xU_z(x, y)dxdy; \\ \bar{y}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U_z(x, y)dxdy &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} yU_z(x, y)dxdy \end{aligned} \tag{17}$$

in which the integrations may be performed over any horizontal plane above V, over which the gravitational field of V, $-U_z(x, y)$, is known. No assumption of homogeneity in V is required for the derivation of these expressions. As mentioned previously, U_z shall later be related to the residual field g; then, when the explicit connection is known, the substitution can be made into (17). In this particular instance, however, the same result is achieved directly by identifying $-U_z$ with g, i.e.,

$$\begin{aligned} \bar{x}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x, y)dxdy &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} xg(x, y)dxdy; \\ \bar{y}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x, y)dxdy &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} yg(x, y)dxdy. \end{aligned} \tag{18}$$

The validity of these relations is unaffected by inhomogeneity of the mineral deposit; it must be shown that the same is true with regard to the host rock, if their use is to be justified.

Writing (18) in polar coördinates $x+iy=re^{i\theta}$,

$$\bar{x}\overset{\infty}{I}_0 = \overset{\infty}{J}_0, \quad \text{and} \quad \bar{y}\overset{\infty}{I}_0 = \overset{\infty}{K}_0, \tag{19}$$

where

$$\overset{\infty}{I}_0 = \int_0^{\infty}\int_0^{2\pi} g(r, \phi)rd\phi dr, \quad \overset{\infty}{J}_0 = \int_0^{\infty}\int_0^{2\pi} g(r, \phi)\cos\phi r^2 d\phi dr,$$

$$\overset{\infty}{K}_0 = \int_0^{\infty}\int_0^{2\pi} g(r, \phi)\sin\phi r^2 d\phi dr.$$

These integrals may be evaluated with the aid of templates or overlay charts, which may be drawn such that in each segment g may be assigned a mean (con-

stant) value and

$$\int_{r_s}^{r_{s+1}} \int_{\phi_t}^{\phi_{t+1}} \begin{matrix} \sin \phi \\ \cos \phi \end{matrix} r^2 d\phi dr \quad \text{or} \quad \int_{r_s}^{r_{s+1}} \int_{\phi_t}^{\phi_{t+1}} r d\phi dr$$

take simple fractional values. Then the processes of integration are replaced with those of summation according to the scheme

$$\overset{\infty}{\underset{0}{I}} = \sum_{s=0}^{\infty} \sum_{t=0}^{2\pi} \bar{g}(r_{s+1/2}, \phi_{t+1/2} \int_{r_s}^{r_{s+1}} \int_{\phi_t}^{\phi_{t+1}} r d\phi dr, \text{ etc.}$$

It is seldom possible to proceed with the summation very far outward from the centers of the charts, of course, since the boundaries of anomalies are almost always obscured by extraneous influences. If R is the greatest radius within which the data are deemed to be reliable, the integrations may be performed only out to this ring. Beyond R, there is assumed to be negligible contribution from the multipole moments of V higher than order zero; i.e., the body is assumed to behave as a point mass. R must be greater than z_0, otherwise quantitative interpretation is not warranted by the data.

If the anomalous mass of the body is M, then its gravitational potential at a point P in the datum plane whose distance from the origin is $r > R$, is

$$U_p \leqq GM/(r^2 + \bar{r}^2 - 2r\bar{r} \cos \gamma)^{1/2}.$$

where $\bar{r}$ is the distance from the origin to the center of gravity and γ is the angle contained by $\bar{r}$ and r. According to (2) and (3),

$$\begin{aligned} U_p &= (GM/r) \sum_{l=0}^{\infty} (\bar{r}/r)^l P_l(\cos \gamma) \\ &= (GM/r) \sum_{l=0}^{\infty} 4\pi/(2l + 1) \sum_{m=-l}^{m=l} (\bar{r}/r)^l y_l{}^{m*}(\bar{\theta}, \bar{\phi}) y_l{}^m \left(\frac{\pi}{2}, \phi\right) \end{aligned}$$

where $(\bar{\theta}, \bar{\phi})$ are the polar angles of $\bar{r}$, and $(\pi/2, \phi)$ those of r.

If we write for convenience

$$\overset{\infty}{\underset{0}{I}} = \int_0^{\infty} \int_0^{2\pi} g(r, \phi) r dr d\phi$$

and

$$\overset{\infty}{\underset{0}{H}} \equiv \overset{\infty}{\underset{0}{J}} + i \overset{\infty}{\underset{0}{K}} = \int_0^{\infty} \int_0^{2\pi} g(r, \phi) e^{i\phi} r d\phi dr,$$

where, for $r > R$,

$$\begin{aligned} g(r, \phi) &= - \partial/\partial z U_p \Big|_{z=0} \\ &= 4\pi GM \sum_{l=0}^{\infty} \frac{1}{2l + 1} \left(\frac{\bar{r}}{r}\right)^l \sum_{m=-l}^{m=l} y_l{}^{m*}(\bar{\theta}, \bar{\phi}) \left[\frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} y_l{}^m(\theta, \phi)\right]_{\theta=\pi/2} \end{aligned}$$

then

$$\overset{\infty}{I}_R = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} \overset{\infty}{I}_R{}^{l}{}^{m},$$

and

$$\overset{\infty}{H}_R = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} \overset{\infty}{H}_R{}^{l}{}^{m},$$

where

$$\overset{\infty}{I}_R{}^{l}{}^{m} = \frac{4\pi GM}{2l+1} \bar{r}^{l} y_l{}^{m*}(\bar{\theta}, \bar{\phi}) \int_R^{\infty} \int_0^{2\pi} \frac{1}{r^{l+1}} \left[\frac{1}{\sin\theta} \frac{\partial}{\partial\theta} y_l{}^{m}(\theta, \phi) \right]_{\theta=\pi/2} d\phi dr \qquad (20)$$

and

$$\overset{\infty}{H}_R{}^{l}{}^{m} = \frac{4\pi GM}{2l+1} \bar{r}^{l} y_l{}^{m*}(\bar{\theta}, \bar{\phi}) \int_R^{\infty} \int_0^{2\pi} \frac{1}{\rho^{l}} \left[\frac{1}{\sin\theta} \cdot \frac{\partial}{\partial\theta} \cdot y_l{}^{m}(\theta, \phi) \right]_{\theta=\pi/2} e^{i\phi} d\phi d\rho. \qquad (21)$$

Now

$$\left[\frac{1}{\sin\theta} \frac{\partial}{\partial\theta} y_l{}^{m}(\theta, \phi) \right]_{\phi=\pi/2} = -Ce^{im\phi} \left[\frac{d}{dx} P_l{}^{|m|}(x) \right]_0,$$

where C is the normalizing factor

$$C = \left[\frac{2l+1}{4\pi} \frac{(l-|m|)!}{(l+|m|)!} \right]^{1/2},$$

and so integration with respect to ϕ removes all of the terms (20) but those in which $m=0$, and all of the terms (21) but those in which $m=-1$.

Also,

$$\left[\frac{d}{dx} P_l(x) \right]_{x=0} = lP_{l-1}(0) = 0 \quad \text{for} \quad l = 0, 2, 4, \cdots$$

and

$$\left[\frac{d}{dx} P_l'(x) \right]_{x=0} = 0 \quad \text{for} \quad l = 1, 3, 5 \cdots,$$

so that the only contributions to $\overset{\infty}{I}_R$ will be from $\overset{\infty}{I}_R{}^{1}{}^{0}$, $\overset{\infty}{I}_R{}^{3}{}^{0}$, etc.; and to $\overset{\infty}{H}_R$, from

$\overset{\infty}{H}_R{}^{2}{}^{-1}$, $\overset{\infty}{H}_R{}^{4}{}^{-1}$, etc.

From (20) and (21) it appears that, if it is admitted that $\bar{x}^2+\bar{y}^2 \ll \bar{z}^2$ (which will generally be true if the origin of coördinates is placed in the close vicinity of the anomaly peak)

$$\underset{0}{\overset{\infty}{I}} = \left[1 - \frac{|z_0|}{R} + \frac{|z_0|^3}{2R^3} + \cdots + O\left(\frac{|z_0|^5}{R^5}\right)\right]^{-1} \underset{0}{\overset{R}{I}} \tag{22}$$

and

$$\underset{0}{\overset{\infty}{H}} = \left[1 - \frac{3|z_0|}{2R} + \frac{5|z_0|^3}{4R^3} + \cdots + O\left(\frac{|z_0|^5}{R^5}\right)\right]^{-1} \underset{0}{\overset{R}{H}} \tag{23}$$

these two series are sufficiently rapidly convergent that the first three terms give a satisfactory result. However, the further problem is raised of making a preliminary estimate of z_0. It is not necessary to know it with great accuracy, and the following method has been found to give values that are sufficiently precise.

As is well known, a horizontal density distribution can be constructed at any depth less than some critical value to account for a given gravitational field (Green's Theorem: Tsuboi and Fuchida, 1938). The gravitational field of a non-extended structure can always be extrapolated downward by this process to the depth of the center of gravity, but it may not be continued much below. The rigorous proof of this statement would be difficult, but it seems intuitively clear. Thus the maximum depth at which a surface distribution of mass can be constructed to account for a given gravitational field should prove to be a fair estimate of the depth to the center of gravity of the "three-dimensional" body producing the field. Carrying the entire field downward, however, is an intricate and laborious business, involving, as it does, a very great deal of harmonic analysis. For most practical purposes it is sufficient to choose the steepest gradient through the point of maximum anomaly, and the gradient at right angles to this. If the half-widths of the anomaly in these two directions are λ_m and μ_m, then the greatest "wavelengths" to be found among the double Fourier components of the anomaly resolved in these two directions will be roughly $2\lambda_m$ and $2\mu_m$. Of course, there is little physical significance in the use of the word "wavelength" unless it is assumed that the anomaly has a periodic character, but this is a point that needs no discussion here.

The field

$$g_{pq}(x, y) = A_{pq} \cos px \cos qy$$

can be produced by a horizontal distribution of mass at depth z whose density is

$$\rho_{pq}(x, y) = (A_{pq}/2\pi G)e^{\sqrt{p^2+q^2}z} \cos px \cos qy,$$

i.e.,

$$g_{pq}(x, y) = 2\pi G e^{-\sqrt{p^2+q^2}z} \rho_{pq}(x, y),$$

a result that has been demonstrated by Tsuboi and Fuchida. If the greatest density that can plausibly be ascribed to the surface distribution is ρ_m, then

$$z \leqq (p^2 + q^2)^{-1/2} \log 2\pi G\rho_m/A_{pq}$$

which gives an upper bound for z. The amplitude of the anomaly in the neighborhood of the wavelengths $2\lambda_m$, $2\mu_m$ is about $\frac{1}{2}g_m$, where g_m is the maximum anomaly, and so

$$z_0 \cong \pi^{-1}(1/\lambda_m{}^2 + 1/\mu_m{}^2)^{-1/2} \log 4\pi G\rho_m/g_m. \tag{24}$$

This expression has been found to yield preliminary values of z_0 which are well within the proper order of magnitude, and this is sufficient for our purpose.

The means are now at hand for finding the position on the ground of the center of gravity of any bounded distribution of anomalous material which can account for the residual gravity field, directly from the map of the residual field itself. Because of the importance of this point in all subsequent calculations, however, it is suggested that a number of independent determinations be made and that a least squares (or other) average be used.

9. ADJUSTMENT OF PARAMETERS BY RELAXATION

The calculations of §7 may be regarded as leading to a first approximation, which may then be deformed continuously, as suggested by Gassmann (1948), until its calculated gravity field coincides with the residues observed at a selected number of survey stations. If these points are chosen more or less symmetrically about the peak of the anomaly, the deformed structure can be made to reproduce the observed anomaly pattern in almost all of its essential details.

The calculated gravity field of the theoretical structure at the point (x_i, y_i, z_0) in the datum plane is

$$f_i \equiv -U_z(x_i, y_i) = \sum_{l=0}^{3} \sum_{(m)} B_l{}^{(m)}/R^{2l+3} \cdot h_l{}^{(m)}(x_i, y_i, z_0; \Theta_0, \Psi_0, \Phi_0) \tag{25}$$

where $h_l{}^{(m)}$ are polynomials that are homogeneous in their cartesian and trigonometric arguments, and the moments $B_l{}^{(m)}$ are functions of j parameters λ_j. The coordinates relate to the observer's frame of reference, and the subscripts $_0$ denote the initial solutions yielded by the formulae (11)–(16).

If these parameters and the Eulerian angles are allowed to suffer a small change, then

$$\Delta f_i = \sum_{l=0}^{3} \sum_{(m)} \sum_{j} \frac{h_l{}^{(m)}}{R^{2l+1}} \left.\frac{\partial B_l{}^{(m)}}{\partial \lambda_j}\right|_{(\lambda j)_0} \Delta\lambda_j$$
$$+ \sum_{l=0}^{3} \sum_{(m)} \frac{B_l{}^{(m)}}{R^{2l+1}} \left[\left.\frac{\partial h_l{}^{(m)}}{\partial \Theta}\right|_{\Theta_0} \Delta\Theta + \left.\frac{\partial h_l{}^{(m)}}{\partial \Psi}\right|_{\Psi_0} \Delta\Psi + \left.\frac{\partial h_l{}^{(m)}}{\partial \Phi}\right|_{\Phi_0} \Delta\Phi \right] \tag{26}$$

to a close approximation.

Suppose that (x_i, y_i, z_0) lies at a station where the recorded residue is g_i. Then writing

$$\Delta f_i = g_i - f_i \tag{27}$$

at a minimum of $j+3$ stations gives linear algebraic equations in $\Delta\lambda_i$, $\Delta\Theta$, $\Delta\Psi$, $\Delta\Phi$, which may be solved either by the relaxation method, or by the method of least squares. This process may be repeated as often as may be necessary to reproduce the anomaly pattern with any practical degree of fidelity. In many cases, where the finer details of orientation are of little practical consequence, it may be found unnecessarily tedious to disturb the Eulerian angles, since the parameters defining the size and shape are little affected by them.

10. DISCUSSION

This paper has been concerned with the building of the theoretical framework of a method for interpreting residual gravitational anomalies in terms of possible three-dimensional structures of the geological masses that cause them. The masonry to be added in a second paper will be the development of a technique in the treatment of data for the practical utilization of this method, and the application of the system as a whole to actual and to artificial problems. The partition is desirable in view of the entire length of the work, and this seems to be the logical point of interruption.

There is the danger, however, that because the stage of development has not been reached when practicability can be discussed, many readers may feel that this paper is an academic exercise, and will have little practical value. Partly in an endeavor to forestall this opinion, and partly out of the wish to make the manuscript more attractive to the many readers who may find it difficult to visualize the physical concepts that underlie mathematical presentations, the following descriptive compend is offered.

Suppose that an observer sets out to measure the gravitational (or other potential) field of a non-uniform, irregularly-shaped body, be it a geological mass, a ship's hull, or a piece of farm machinery. Beyond a certain distance from the object, his instrument will be unable to distinguish it from a point mass. But if he should step within this radius his instrument will begin to record some asymmetry in the field. However, as long as he remains beyond a second critical distance from the body, his measurements can be reproduced exactly (i.e., within the practical limit of resolution of the instrument) by a triple of mutually perpendicular dipoles of given strengths superposed over the point mass. With no previous knowledge of the object, he can deduce from measurements taken within this range its mass and its dipole moments and nothing more; but these are determined uniquely. If he continues to approach the body, he will find that within a third well-defined range of distances his observations can be reproduced exactly by a quintuple of mutually perpendicular quadrupoles of given strengths superposed over the dipoles and the point mass, and within a fourth range a septuple of octupoles must be added. In virtually every problem of practical importance in exploration geophysics, the observer will never find himself within the fourth critical distance, and so at all times the body, to practical instruments, is indistinguishable from a point mass and a superposition of dipoles, quadrupoles, and octupoles.

Now if the body has a simple shape or more realistically, if we are content to approximate it to a simple shape, which is tantamount to assuming that the body can be fully described by a very few parameters, then these multipoles take on a very useful significance, for their moments become very simple functions of the parameters which describe the body. Therefore, since these moments are determined uniquely by field measurements, one would expect that if we can devise a means for reckoning from the field the relative strengths of as many moments as there are parameters (and this number must be chosen *a priori*), then, from a knowledge of the physical property contrast between the body and its surroundings, the parameters themselves can easily be deduced. An initial guess at the values of the moments is obtained from the formulae in §7, and this result may subsequently be "tuned up" quite systematically to give agreement over the whole field by the method of relaxation described in §9. As in any other relaxation method, the convergence of the numerical calculations is slow if the initial guess is a bad one; and rapid if it is good. That is why it always pays in the long run to take a great deal of care in finding the position of the center of gravity and in calculating the derivatives there, and why a special technique that permits the careful computation of these quantities is quite indispensable to the method.

From what has been said, it is clear that the successful application of multipole analysis to practical problems does not require data of unusually high quality or precision. Random errors in the data can be taken care of for the most part in exactly the same way as random density fluctuations in the country rock, for the observed effects are identical; moreover, some discrimination may be practised in the selection of points of relaxation. The more serious (and often unavoidable) errors resulting from systematic aberrations may be ground down to some extent by the relaxation process. These points are all obvious, but they deserve to be underscored.

And finally, the interpreter will find that he is not restricted to the use of a single form of structure to represent the unknown body, but may express his findings with equal accuracy and facility through a whole range of models, thus leaving room for the exercise of a certain amount of particular judgment in individual geological cases. The entire procedure probably will be used to its fullest extent when geological controls are lacking, but even if such controls should exist it can be made to yield ancillary information which may be quite useful.

APPENDIX I

CALCULATION OF REDUCED MULTIPOLE MOMENTS OF SOME EXAMPLES

$$b_0^0 = \sqrt{4\pi}\, G\rho \int_V d^3x_0$$

$$b_1^0 = \sqrt{\frac{4\pi}{3}}\, G\rho \int_V z d^3x_0$$

$$b_1^{\pm 1} = \frac{1}{2}\sqrt{\frac{4\pi}{6}}\, G\rho \int_V (x_0 \pm iy_0) d^3x_0$$

$$b_0^2 = \frac{1}{2}\sqrt{\frac{4\pi}{5}}\, G\rho \int_V (2z_0^2 - x_0^2 - y_0^2) d^3x_0$$

$$b^{\pm 1} = \sqrt{\frac{3}{2}}\sqrt{\frac{4\pi}{5}}\, G\rho \int_V (z_0 x_0 \pm iz_0 y_0) d^3x_0$$

$$b_2^{\pm 2} = \frac{1}{2}\sqrt{\frac{3}{2}}\sqrt{\frac{4\pi}{5}}\, G\rho \int_V (x_0^2 - y_0^2 - 2ix_0y_0) d^3x_0, \text{ etc.}$$

1) *Circular Cylinder:* (Tetragonal Class) z' axis along the axis of rotation, origin at geometrical center.

$$B_0^0 = G\rho\pi R^2 L, \qquad B_2^0 = G\rho\pi R^2 L(L^2/3 - R^2)$$

2) *Ellipsoid of Revolution:* (Tetragonal Class) Axes prescribed as above.

$$B_0^0 = \frac{4}{3}\pi G\rho a^2 b, \qquad B_2^0 = \frac{1}{15} G\rho\pi a^2 b(b^2 - a^2).$$

3) *Elliptical Cylinder:* (Orthorhombic Class) z' axis along the cylindrical axis, origin at center, x' and y' axes along the elliptical axes.

$$B_0^0 = G\rho\pi abL, \quad B_2^0 = \frac{1}{6} G\rho\pi abL(2L^2 - a^2 - b^2), \quad B_2^2 = \frac{1}{4} G\rho\pi abL(a^2 - b^2).$$

4) *Rectangular Parallelopiped:* (Orthorhombic Class) Origin at the geometrical center, x', y', z' axes along axes of symmetry.

$$B_0^0 = G\rho abc, \qquad B_2^0 = \frac{1}{48} G\rho abc(2c^2 - b^2 - a^2), \qquad B_2^2 = \frac{1}{32} G\rho abc(a^2 - b^2).$$

5) *Symmetrical Wedge:* (Monoclinic Class) z' axis along the axis of twofold rotational symmetry, origin at center of gravity.

$$B_0^0 = G\rho 2amc^2, \qquad B_1^0 = 0$$

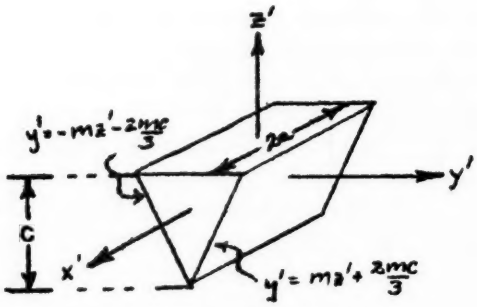
$$B_2^0 = \frac{1}{36} mac^2(2c^2 - 6a^2 - 3m^2c^2)G\rho$$

$$B_2^2 = \frac{1}{8} G\rho mac^2(2a^2 - m^2c^2),$$

etc. for

$$b_3^0 = \frac{1}{2}\sqrt{\frac{4\pi}{7}}\,G\rho\int_V z_0(2z_0^2 - 3x_0^2 - 3y_0^2)d^3x_0,$$

$$b_3^{\pm 2} = \frac{1}{2}\sqrt{\frac{15}{2}}\sqrt{\frac{4\pi}{7}}\,G\rho\int_V z_0(x_0^2 - y_0^2 \pm 2ix_0y_0)d^3x_0.$$



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SUBSURFACE GRAVITY MEASUREMENTS*

GEORGE R. ROGERS†

ABSTRACT

Gravity data were obtained at approximately 100-foot intervals in a vertical mine shaft 2,916 feet deep. The shaft passed through a region of high positive density contrast, and a local anomaly was observed of plus 14.0 gravity units to minus 17.9 gravity units. Calculations for Bouguer densities were carried out with the gravity measurements. A theoretical sphere that closely approximates the observed data and known conditions is derived from the gravity data.

The potential value of vertical gravity "logs" and underground gravity patterns as a further key to geologic conditions has been discussed in considerable detail by Hammer (1) and Smith (2). In furtherance of these studies, an example of a vertical gravity log that passes through an anomalous region is presented here.

A series of gravity observations was made in a vertical mine shaft in Arizona during the winter (1950–1951). The work was done at the suggestion of and with excellent cooperation by Mr. S. P. Worden of the Houston Technical Laboratories. Gravity measurements were made at approximately 100-foot intervals from the surface to a depth of 2,916 feet.

The gravity values are a compilation of data from three Worden gravity meters and one Frost meter. A tabulation of the raw data indicating the source is shown in Table I. The gravity stations are identified by numbers corresponding to their distance in feet below the collar of the shaft. The data obtained with Worden meters *A* and *B* are of particular interest. These readings, down to Station 1242, were made on a dinky cage. Conditions under which these readings were taken were quite adverse for both meter and operator. The cage was very unsteady and a rapid flow of cold ventilation air down the shaft caused further unsteadiness of the meter. Extreme variations in air temperature and pressure were encountered. In spite of these difficulties the quality of the data is good. The two meters were operated simultaneously on the cage floor. It is interesting to note that useful gravity data can be obtained from a gravity meter essentially suspended by 1,200 feet of wire rope. Elevations were obtained from a marked piano wire suspended in the shaft. The data from these two meters had an average difference of 0.6 gravity units. The remainder of the data was obtained from firm tripod "set-ups" in mine workings. In all cases the meter was (1) positioned so as to cause near cancellation of gravity effects from mine workings and (2) within 20 feet, horizontally, of the shaft center line. The data from the Frost meter were

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TABLE I

RAW GRAVITY DATA IN GRAVITY UNITS STATIONS IDENTIFIED BY DISTANCE BELOW COLLAR OF SHAFT IN FEET

Gravity Station	Worden "A"	Worden "B"	Worden "C," Run 1	Worden "C," Run 2	Frost C-3-65	Average
0	40.7	40.7	40.7[b]	40.7[b]		40.7
−98	74.5	72.4	—	—	—	73.4
−198	98.1	100.1	—	—	—	98.8
−300	122.8	122.8	—	—	—	122.8
−400	147.2	147.8	—	—	—	147.5
−500	173.0	173.4	—	—	—	173.2
−599	197.1	197.3	—	—	—	197.2
−700	221.3	220.2	—	—	—	220.7
−800	246.4	246.5	—	—	—	246.5
−902	272.3	272.1	—	—	—	272.2
−1002	296.3	296.6	—	—	—	296.5
−1102	322.0	321.8	—	—	—	321.9
−1200	346.8	346.1	—	—	—	346.4
−1242	356.2[a]	355.8[a]	356.5	356.1	—	356.2
−1360	—	—	386.9	387.4	—	387.2
−1456	—	—	411.4	411.2	—	411.3
−1555	—	—	437.4	437.2	—	437.3
−1654	—	—	464.5	464.7	—	464.6
−1753	—	—	492.7	492.4	—	492.6
−1854	—	—	521.9	521.8	—	521.9
−1958	—	—	547.3	547.0	—	547.2
−2057	—	—	568.0	568.1	—	568.1
−2155	—	—	585.2	585.2	—	585.2
−2257	—	—	—	—	600.5[d]	600.5
−2383	—	—	—	—	629.0[d]	629.0
−2517	—	—	—	—	663.2[d]	663.2
−2650	—	—	—	—	694.3[d]	694.3
−2783	—	—	—	—	727.0[d]	727.0
−2916	—	—	—	—	759.8[d]	759.8
−2650A	—	696.6	696.7[e]	—	696.7[d]	696.7

[a] Converted from Station −1247.
[b] Converted from Station +4.0.
[e] Established by 3 direct gravity differences.
[d] Average of multiple values obtained with Frost meter from closed base loop data including Station −2650A.

obtained previously in the course of lateral exploration surveys. A precise tie to the Worden data is available at the auxiliary Station 2650A. The independent calibration of the Frost and Worden meters was compared through their respective indications over a gravity difference of 650 gravity units. The calibration was equivalent to 1 part in 1000 which is sufficient for the present purpose. No ties to absolute gravity nets have been made and the values are presented relative to surface Station O.

As has been previously pointed out, particularly by Smith (2) and Hammer (1), a vertical gravity log will be influenced by the effective Bouguer density of the intervals traversed and by any local anomalies present. Assume that suitable corrections have been applied to the observed gravity, G_0, for topography and any voids surrounding the points of observation. This yields "corrected" gravity des-

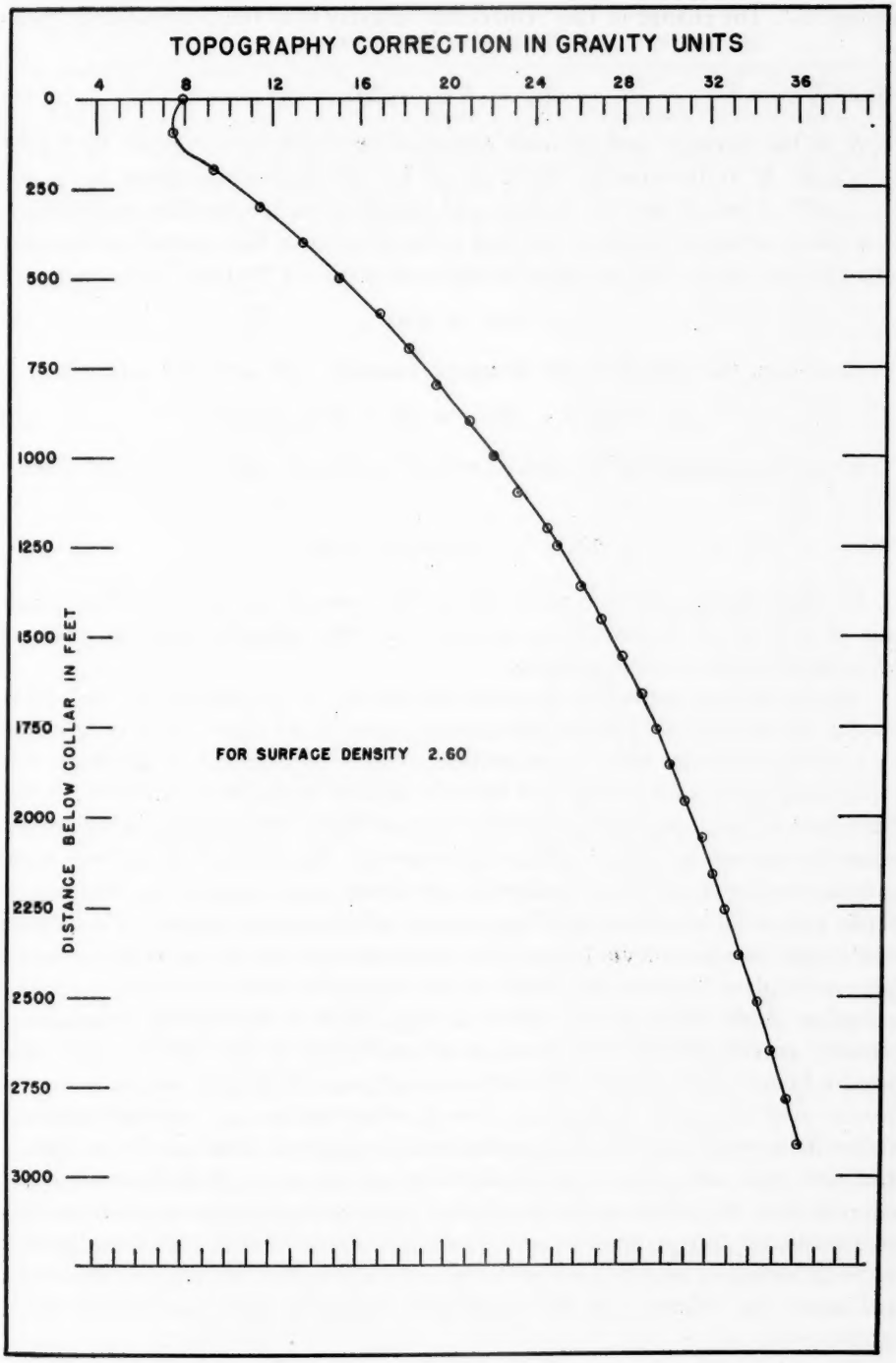

FIG. 1. Plot of the topography correction versus depth.

ignated G_0'. The change in this "corrected" gravity over the interval Δz is given by

$$\Delta G_0' = K'\Delta z + \Delta D. \tag{1}$$

K is the average underground elevation or depth factor given by $(.9406 - .2552d)$. K' is the specific depth factor for the interval Δz given by $(.9406 - .2552d')$. d and d' are the average and specific Bouguer densities respectively. D is the anomalous function, and ΔD is the change in the anomalous function over the interval Δz. The Bouguer formula will predict a "normal" change of

$$\Delta G_n' = K\Delta z. \tag{2}$$

Therefore, the change in the Bouguer anomaly, ΔB, over the interval Δz is

$$\Delta B = (\Delta G_0' - \Delta G_n') = (K' - K)\Delta z + \Delta D. \tag{3a}$$

K' can be expressed as $(K+\Delta K)$, hence $K'-K$ is ΔK. $\Delta K = -.2552\Delta d$. Therefore

$$\Delta B = -.2552\Delta d\Delta z + \Delta D. \tag{3b}$$

If either the density increment, Δd, or the anomaly increment, ΔD, of equation $3b$ is known it is possible to evaluate the other quantity with the value of ΔB from the gravity measurements.

The corrections applied to the observed gravity, G_0, to obtain corrected gravity, G_0', are shown on Table II. The gravity effect of the shaft was approximated by a vertical cylinder with a cross section equal in area to that of the shaft. The topography correction is large and shows a marked variation with depth. Figure 1 is a plot of the topography correction versus depth. This correction was determined by the method described by Hammer (3). The sizes of the various compartments were modified to make the graticule more suitable for stations at depth and to handle the rugged topography of this mining district. Corrections were applied so as to level topography within 65,150 feet of the stations onto a horizontal plane through the collar of the shaft. In order to obtain a smooth variation of the topography correction with depth it was found necessary to tabulate gravity effects for the various compartments to 0.01 gravity units. The usual tabulation is 0.1 unit with each compartment subject to a maximum random error of 0.05 units. In this type of work, where stations are oriented vertically at 100 ft intervals and the topography itself is rugged, it was found that the cumulative error using the 0.1 unit tabulation was excessive. This follows by considering that the difference in cumulative error between adjacent stations may be considerably larger than the absolute value of this error at a single station. It is the difference in gravity between adjacent stations that is critical in this work, and hence the difference in the topography correction must be carefully determined.

The calculations shown on Table III are carried forward in the usual manner

TABLE II

CORRECTIONS IN GRAVITY UNITS

Station	Observed Gravity G_0	Shaft	Topography	Corrected Gravity G_0'
0	40.7	+2.3	+7.9	50.9
98	73.4	+0.1	7.4	80.9
198	98.8	—	9.3	108.1
300	122.8	—	11.4	134.2
400	147.5	—	13.4	160.9
500	173.2	—	15.1	188.3
599	197.2	—	16.8	214.0
700	220.7	—	18.2	238.9
800	246.5	—	19.5	266.0
902	272.2	—	21.0	293.2
1002	296.5	—	22.1	318.6
1102	321.9	—	23.2	345.1
1200	346.4	—	24.4	370.8
1241	356.2	—	24.9	381.1
1360	387.2	—	26.1	413.3
1456	411.3	—	27.1	438.4
1555	437.3	—	28.1	465.4
1654	464.6	—	29.0	493.6
1753	492.6	—	29.6	522.2
1854	521.9	—	30.3	552.2
1958	547.2	—	31.0	578.2
2057	568.1	—	31.8	599.9
2155	585.2	—	32.3	617.5
2257	600.5	—	32.8	633.3
2383	629.0	—	33.6	662.6
2517	663.2	—	34.3	697.5
2650	694.3	—	35.0	729.3
2784	727.0	—	35.7	762.7
2916	759.8	−0.2	36.4	796.0

to obtain the Bouguer anomaly, B. The overall depth factor used to calculate G_n' was determined by the gravity difference between the surface and Station 2650. An extensive lateral survey in mine workings at that depth permitted a reliable evaluation of the anomalous function, D. No significant anomalies affect the surface station. The K so determined was 0.2596 gravity units per foot which corresponds to an overall Bouguer density of 2.67. After the Bouguer anomaly was determined, equation $3b$ was applied to calculate apparent densities by ignoring the ΔD term. If, on the other hand, the density variations were ignored, ΔB would be identical to ΔD and the recorded Bouguer anomaly would also be the local anomaly.

Figure 3 is a plot of the Bouguer anomaly and it is apparent from this that significant non-Bouguer gradients exist. Before further considering Figure 3 several points regarding geology and density contrasts should be brought out. Below a depth of 167 feet the shaft is in limestone, some of which is mineralized. The density of 50 hand samples of unmineralized limestone ranged from a low of 2.67 to a high of 2.76 and averaged 2.71. There was no apparent correlation between hand sample density and either formation or depth. Of the various rock types in the area, only the surface soil and conglomerate, and the mineralized

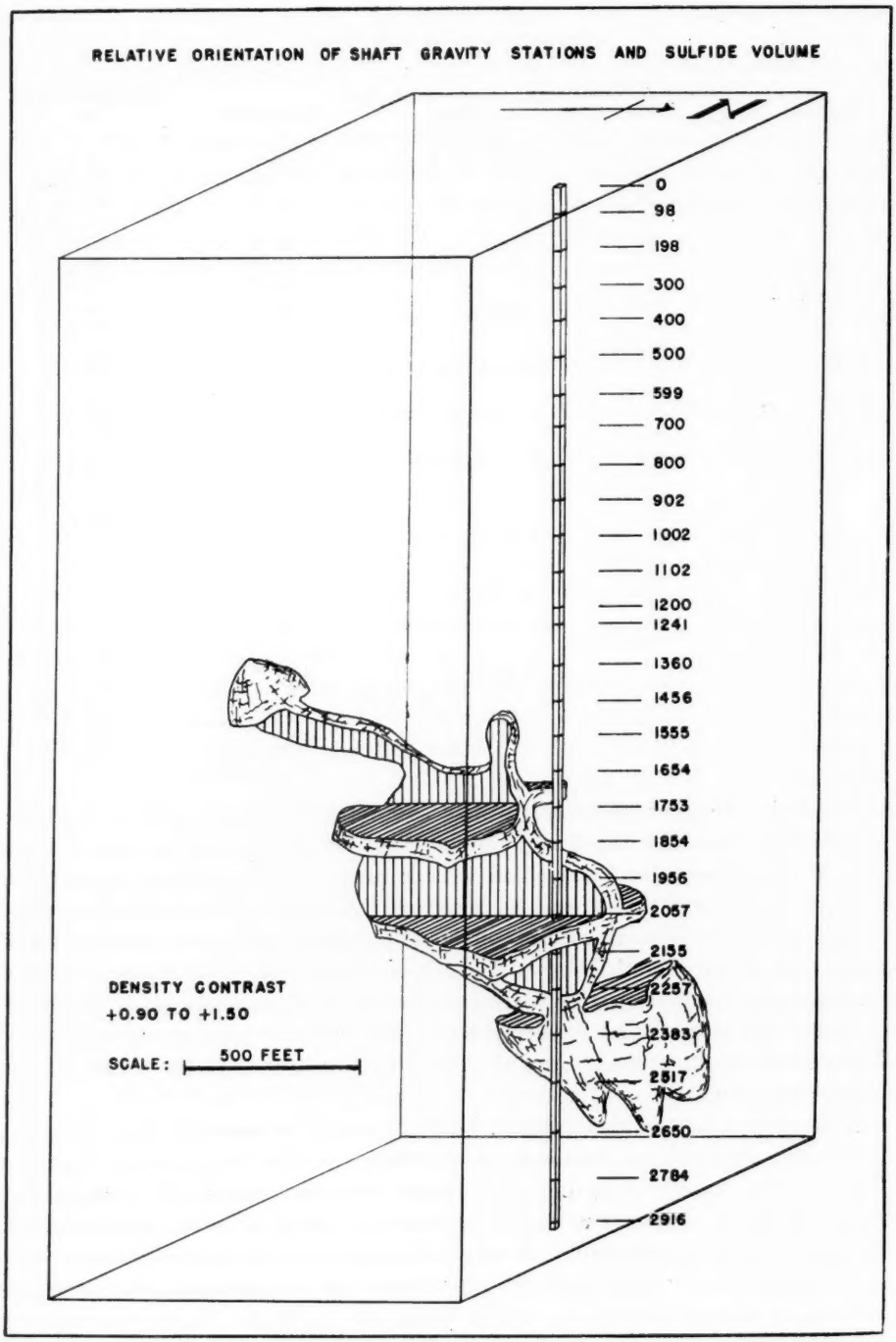

FIG. 2. Orientation and shape of sulfide mass shown in a truncated isometric view.

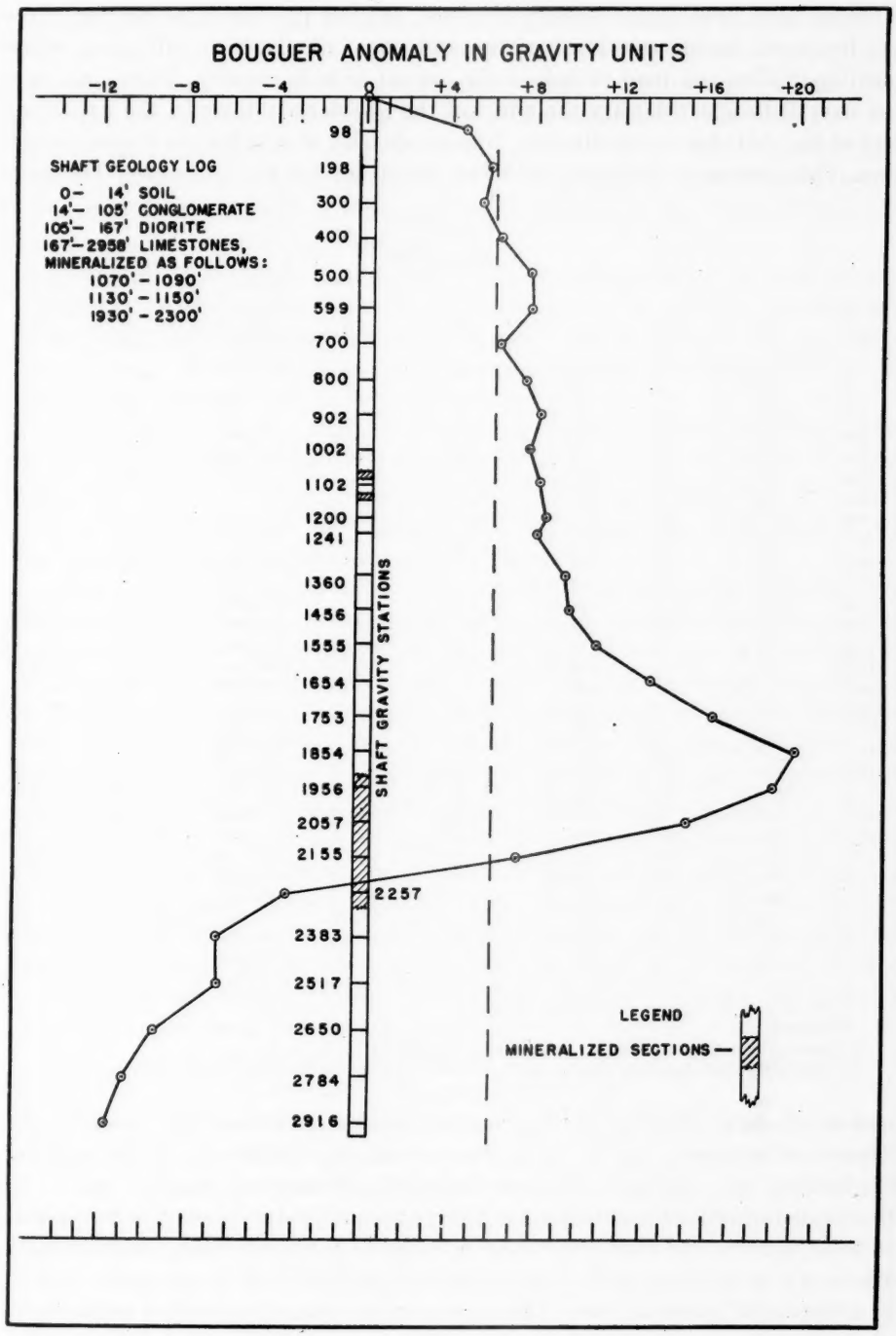

FIG. 3. Plot of the observed Bouguer anomaly.

sections have appreciable density contrast. Within the limestone section there are fractures, faults, solution cavities, and vugs, all of which will cause minor local anomalies and tend to reduce the overall or bulk density. Removing from the overall Bouguer density the effect of the low density layer in the upper 200 feet of the shaft leaves an effective Bouguer density of 2.68 for the limestone section. This compares favorably with the density of the hand samples. The sedi-

TABLE III

CALCULATIONS

Station (z)	G_0'	Δz	G_n*	B*	ΔB	$\Delta B/\Delta z$	Δd	d
0	50.9	0	50.9	0†				
−98	80.9	98	76.3	+4.6	+4.6	+.047	−.18	2.49
−198	108.1	100	102.3	+5.8	+1.2	+.012	−.05	2.62
−300	134.2	102	128.8	+5.4	−0.4	−.004	+.02	2.69
−400	160.9	100	154.7	+6.2	+0.8	+.008	−.03	2.64
−500	188.3	100	180.7	+7.6	+1.4	+.014	−.05	2.62
−599	214.0	99	206.4	+7.6	0	0	0	2.67
−700	238.9	101	232.6	+6.3	−1.3	−.013	+.05	2.72
−800	266.0	100	258.6	+7.4	+1.1	+.011	−.04	2.63#
−902	293.2	102	285.1	+8.1	+0.7	+.007	−.03	2.64#
−1002	318.6	100	311.0	+7.6	−0.5	−.005	+.02	2.69#
−1102	345.1	100	337.0	+8.1	+0.5	+.005	−.02	2.65#
−1200	370.8	98	362.4	+8.4	+0.3	+.003	−.01	2.66#
−1241	381.1	41	373.1	+8.0	−0.4	−.010	+.04	2.71##
−1360	413.3	119	404.0	+9.3	+1.3	+.011	−.04	2.63#
−1456	438.4	96	428.9	+9.5	+0.2	+.002	−.01	2.66#
−1555	465.4	99	454.6	+10.8	+1.3	+.013	−.05	2.62#
−1654	493.6	99	480.3	+13.3	+2.5	+.025	−.10	2.57#
−1753	522.2	99	506.0	+16.2	+2.9	+.029	−.11	2.56#
−1854	552.2	101	532.2	+20.0	+3.8	+.038	−.15	2.52#
−1958	578.2	104	559.2	+19.0	−1.0	−.001	+.00	2.67#
−2057	599.9	99	584.9	+15.0	−4.0	−.040	+.16	2.83#
−2155	617.5	98	610.3	+7.2	−7.8	−.080	+.31	2.98#
−2257	633.3	102	636.8	−3.5	−10.7	−.105	+.41	3.08#
−2383	662.6	126	669.5	−6.9	−3.4	−.026	+.10	2.77#
−2517	697.5	134	704.3	−6.8	+0.1	+.001	−0.0	2.67#
−2650	729.3	133	738.8	−9.5	−2.7	−.020	+.08	2.75#
−2784	762.7	134	773.6	−10.9	−1.4	−.010	+.04	2.71#
−2916	796.0	132	807.9	−11.9	−1.0	−.008	+.03	2.70#

* For normal density of 2.67 (.2596 gu/ft.)
† Assumed.
# Density figure invalid due to non-Bouguer gradients.
Density figure doubtful due to short Δz interval and non-Bouguer gradients.

mentary beds are dipping 20 to 30 degrees, and there are numerous major faults. Therefore, because of (1) the lack of density change (2) the dip of the beds and (3) faulting, no correlation between the gravity determined density log and the limestone formations is anticipated. A large mineralized volume of rock is known to be adjacent to the shaft and can be expected to produce a strong local anomaly. Figure 2 is an attempt to show the shape and orientation of this irregular volume in a truncated isometric view. The mineralization consists of sulfide replacement of the limestone and is largely pyrite with associated chalcopyrite, bornite, chal-

cocite, sphalerite, and galena. Unfortunately there are several features about this sulfide body that makes it very poorly suited for theoretical gravity calculations.* Besides having a very irregular shape, the intensity of mineralization, and therefore the density, increases gradationally as the main mass is approached. Even within the main mass the density varies quite widely, and extensive mining operations have further complicated the picture. The assignment of suitable boundaries and densities as well as the actual integration of the gravity pattern for this volume would be exceedingly difficult.

The density of sulfide hand samples vary from less than 2.8 to more than 7.1 depending partially upon the kind of mineralization but mainly upon how completely the limestone is replaced. The volume shown in Figure 2 has an approximate average density contrast between +0.90 and +1.50 relative to the unmineralized limestones.

Refer again to Figure 3 and the density log of Table III. The sharp increase in *B* between Stations 0 and 98 is definitely due to the low density surface layer composed of soil and conglomerate. The further increase in *B* between Stations 98 and 198 is a reflection of the dipping surface layer and may also be due, in part, to an unconformity between the conglomerate and diorite.

The first distinct appearance of the local anomaly is between Stations 1241 and 1360, although there is no doubt that for some distance above this point the anomalous gradient is modifying the density log. It should be observed that the local anomaly deviates from about the +6.0 gravity unit value rather than from the ordinate. The first appreciable influence of the local anomaly is inferred to be between Stations 700 and 800. This point is poorly defined, largely because of an inherent "noise level" in the barren limestone. A maximum positive anomaly of 20.0 gravity units out of the +6.0 value or +14.0 gravity units was recorded at Station 1854. Note the location of Station 1854 on Figure 2. In passing through the sulfide section the anomaly swings negative quite rapidly. The anomalous gradient between Stations 2155 and 2257 is .105 gravity units per foot. The maximum negative anomaly was recorded at the lowermost station and is −11.9 units out of +6.0 or −17.9 gravity units. There is no necessity for the positive and negative cycles to be equal in amplitude when the causative mass is asymmetrical and of variable density. It cannot be established that this point represents the negative peak because of the lack of deeper gravity data. Station 2916 is the lowest accessible point in the shaft.

The ultimate in this type of work would be a complete three dimensional gravity pattern including contours on vertical as well as horizontal planes. With such a pattern, local anomalies and Bouguer density changes could be differentiated more easily. It is also believed that more definitive data regarding regional trends would result, and that valuable information would be given regarding the nature of gravity anomalies from bedrock topography in areas of relatively thin cover. The problem of limited access will preclude such detailed information, but

* See Appendix.

any multiplicity of underground data in a given area will be of great assistance in interpretation.

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APPENDIX

As previously mentioned, it would be exceedingly tedious to calculate the theoretical anomaly for this sulfide mass from the known geologic distribution. However, it can be seen from Figure 2, that the upper portion of the sulfide mass is reasonably close to spherical shape. Certain properties of spherical masses, which are reviewed below, make it possible to calculate an "effective sphere" that will produce a theoretical anomaly closely approximating the observed anomaly in the upper portions of the curve.

The gravitational acceleration at a point, p, within a homogeneous sphere is proportional to the distance, a, of the point from the center of the sphere. The magnitude of the gravitational acceleration at p within the sphere is due entirely to an interior sphere of radius a; the sphere interior to the point p. The net contribution of the spherical shell, exterior to the radial distance a is zero. Working directly from the formula for the gravitational attraction of a sphere

$$g_z = \frac{4}{3}\pi\kappa dz\left(\frac{R}{r}\right)^3. \tag{4a}$$

For a point on the surface of a sphere, $R=r$ and

$$g_z = 85.3\Delta dz_i, \qquad z_i \leqq R\cos\gamma_0. \tag{4b}$$

The constants are evaluated for distance in kilofeet, g_z in gravity units, and density contrast is substituted for density. Equation 4b is valid for a point on the surface of the sphere where $a=R$, $z_i=R\cos\gamma_0$, and for points interior to the sphere where $z_i=a\cos\gamma$. Figure 4 shows the geometry involved, and a plot of theoretical gravity on vertical traverse lines at various distances from the center of the sphere.

The significant feature is that the vertical gravity gradient within a sphere is linear and is a measure of the density contrast involved. From equation (4*b*) using M for the anomalous gradient in gravity units per 1,000 feet

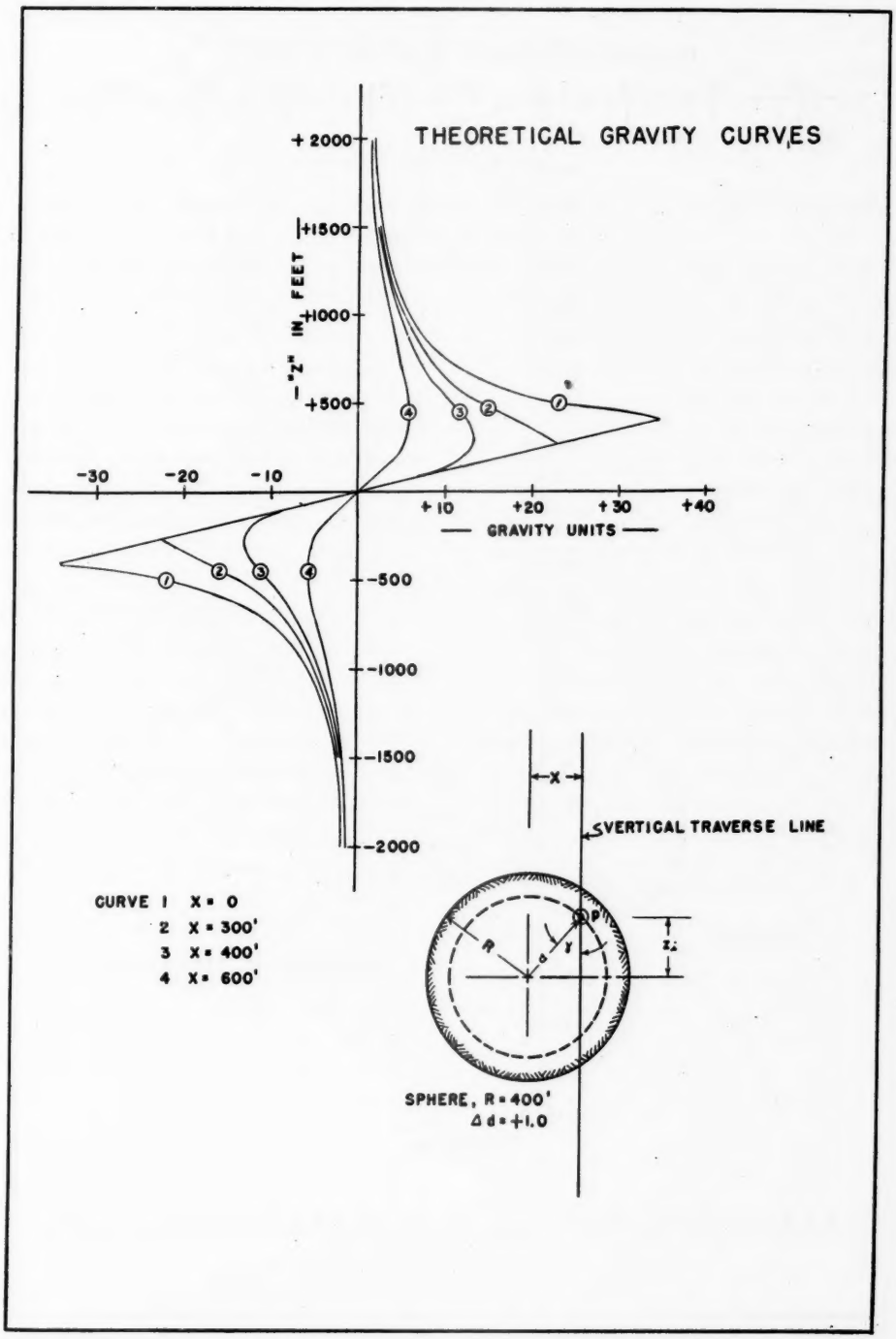

FIG. 4. Sphere in lower right shows dimensions used in the analysis. Theoretical gravity curves for various "x" distances shown in upper left. Slope of linear portion is 85.3 gravity units per 1,000 feet, which corresponds to the assumed density of 1.0.

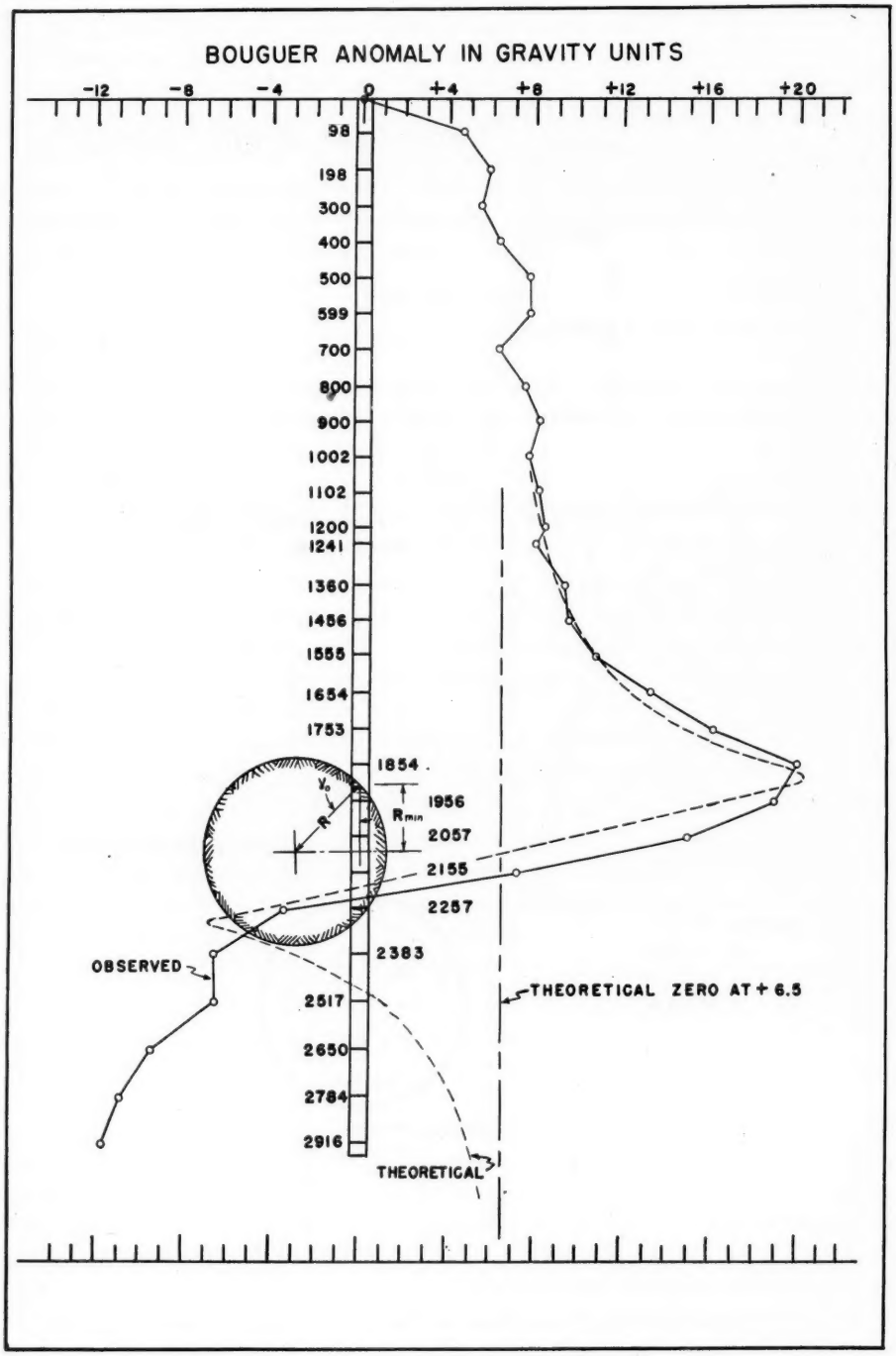

FIG. 5. Comparison of observed gravity with the theoretical gravity calculated for the derived sphere.

$$M = \frac{\Delta g_z}{\Delta z} = 85.3\Delta d$$

or

$$\Delta d = M/85.3. \tag{5}$$

With the value of the density contrast and the gravity curve it is possible to arrive at a value for the radius of the effective sphere.

Consider the present data as an example: In passing through the sulfide section from stations 1958 to 2257 there was a change of 22.5 gravity units. Hence $M = 22.5/.3 = 75$ gravity units per 1,000 feet. The density contrast is $75/85.3 = +0.88$. The maximum anomaly recorded on the upper portion of the curve was +14 gravity units. If the vertical traverse line coincides with the vertical diameter of the sphere, the radius would have to be 185 feet to produce a maximum anomaly of 14 gravity units. This 185 foot value is a "minimum radius" and a larger radius will be required if the vertical traverse line departs from the vertical diameter. On Figure 5 is shown the relation between the minimum radius, R_{Min}, the angle γ_0, and the true radius R. In this case, a reasonable value for γ_0 is 45°, which gives a true radius of 260 feet for the sphere. Figure 5 shows the orientation of the derived "effective sphere" and compares the observed and theoretical anomaly. The two curves are in reasonably good agreement throughout the upper portion of the traverse, where the sulfide mass approaches a spherical shape. The marked departure of the two curves at depth may be explained by known sulfides that extend below the limits of the theoretical sphere. By comparing Figures 5 and 2 it can be seen that the derived sphere is a reasonable approximation of the known conditions. The derived sphere is a bit larger and has a smaller density contrast than indicated on Figure 2. This is explainable on the basis of the gradational increase in density as the main sulfide mass is approached.

THE CYLINDRICAL ORE BODY IN THE PRESENCE OF A CABLE CARRYING AN OSCILLATING CURRENT*

JAMES R. WAIT†

ABSTRACT

The problem of an infinite cable carrying an oscillating current parallel to a conducting cylinder is solved. The homogeneous electrical properties of the media inside and outside the cylinder can be arbitrary. The special case is considered in detail where the exterior medium is a relatively poor conducting medium. The application to geophysical prospecting for massive sulphide ore zones is discussed.

INTRODUCTION

Inductive methods of geophysical prospecting are generally defined as means of investigating the electrical characteristics of subsurface regions by establishing an electromagnetic field by an ungrounded insulated cable carrying a time varying current. The reaction of this field to subsurface regions is studied in an effort to ascertain the variations of electrical properties of these regions.

The best known inductive method was developed originally by Sundberg[1] about 1926. Extensions and improvements have been made by Hedstrom,[2] Zuschlag,[3] and others. The procedure consists essentially in setting up a primary alternating magnetic field by an insulated cable laid out in the form of a large rectangle of the order of 6,000 by 3,000 feet in size, or by a long straight insulated cable which is grounded at both distant ends. The resulting horizontal and vertical magnetic field vectors are then measured at various points in the region of the cable.

The interpretation of these results is usually based on the representation of sub-surface conducting zones as equivalent conducting sheets of small thickness. The theory for the field of an infinite current carrying wire over a conducting sheet has been given by Otto Mayr.[4] It will be the purpose of this present paper to treat another idealized situation which may have a further application for interpretation in the Sundberg method. It will be assumed here that the current cable is parallel or nearly parallel to the strike of a subsurface conducting ore zone which is approximated by a circular cylinder of infinite length.

SOLUTION OF PROBLEM

The following problem will be considered: An infinite wire at O' in Figure 1 carrying a harmonically time varying current $Ie^{i\omega t}$ throughout its length is situated parallel to the axis of a conducting cylinder with radius a and center at O of

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conductivity σ_2, dielectric constant ϵ_2, and magnetic permeability μ_2. The exterior medium is considered to be infinite and homogeneous with conductivity σ_1, dielectric constant ϵ_1 and magnetic permeability μ_1. Polar coordinates (ρ, ϕ, z) with z axis coincident with the axis of the cylinder are chosen. The polar angle ϕ is measured from the plane Ox. The coordinates (ρ_0, ϕ_0) then specify the position of the wire at O'.

The problem now is to calculate the fields at some exterior point $P(\rho, \phi)$ due to the current-carrying wire in the presence of the cylinder. It is evident that the

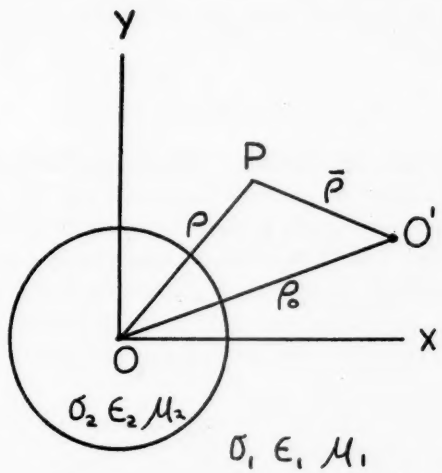

FIG. 1. The coordinate system for the infinite circular conducting cylinder of radius a parallel to a current carrying cable outside the cylinder.

resultant electric fields everywhere have only a component in the z direction. The primary field at P due to the current at O' is well known and given by:

$$E_0(\bar{\rho}) = -\frac{i\mu_1\omega I}{2\pi} K_0(\gamma_1\bar{\rho}), \tag{1}$$

where γ_1 is the propagation constant in the exterior medium given by

$$\gamma_1^2 = i\sigma_1\mu_1\omega - \epsilon_1\mu_1\omega^2$$

and where $K_0(\gamma_1\bar{\rho})$ is the modified Bessel of the third kind of zero order as defined by Watson,[5] (p. 78).

The resultant electric field $E_1(\rho, \phi)$ in the region outside the cylinder will again have only a z component. It will be equal to the sum of the primary field given by $E_0(\bar{\rho})$ and the scattered field $E_1'(\rho, \phi)$. The resultant field inside the cylinder is denoted by $E_2(\bar{\rho}, \phi)$. The resultant fields must be solutions of the two dimensional wave equation

$$\rho \frac{\partial}{\partial \rho}\left(\rho \frac{\partial E_i}{\partial \rho}\right) + \left(\frac{\partial^2}{\partial \phi^2} E_i\right) - \gamma_i^2 \rho^2 E_i = 0, \tag{2}$$

where $i = 1$ or 2, to denote the medium exterior or interior to the cylinder respectively and

$$\gamma_i^2 = i\sigma_i \mu_i \omega^2 - \epsilon_i \mu_i \omega^2.$$

Solutions of the above equation are made up of linear combinations of the following functions:

$$\begin{matrix} I_n & \cos \\ (\gamma_i \rho) & n(\phi - \phi_0) \\ K_n & \sin \end{matrix}$$

where $I_n(\gamma_i \rho)$ and $K_n(\gamma_i \rho)$ are modified Bessel functions of the first and third kind as defined by Watson,[5] p. 77, with argument $\gamma_i \rho$. The solutions containing $\sin n(\phi - \phi_0)$ are not permissible since there is obvious symmetry above the plane containing OO' and the z axis. The solutions containing $K_n(\gamma_i \rho)$ are only permissible outside the cylinder since only they give an outgoing wave at infinity for a time factor $\exp.(iwt)$. The solutions containing $I_n(\gamma_i \rho)$ are only permissible inside the cylinder since the field must be finite at the center of the cylinder for an external source.

The expressions for the electric field outside and inside the cylinder are then given by the following general expressions:

$$E_1 = \sum_0^\infty A_n K_n(\gamma_1 \rho) \cos n(\phi - \phi_0) + E_0 \quad \text{for} \quad \rho \geqq a \tag{3}$$

and

$$E_2 = \sum_0^\infty B_n I_n(\gamma_2 \rho) \cos n(\phi - \phi_0) \quad \text{for} \quad \rho \leqq a, \tag{4}$$

where A_n and B_n are undetermined coefficients which will be determined from the boundary conditions at $\rho = a$. The tangential magnetic field is given everywhere by

$$H_{\phi i} = \frac{1}{i\mu_i \omega} \frac{\partial E_i}{\partial \rho}.$$

Since both the tangential electric and magnetic fields must be continuous across the boundary, in the absence of any surface currents, the following two equations are obtained:

$$\left.\begin{aligned} \frac{1}{\mu_1} \frac{\partial E_1}{\partial \rho} &= \frac{1}{\mu_2} \frac{\partial E}{\partial \rho} \\ E_1 &= E_2 \end{aligned}\right\} \rho = a. \tag{5}$$

In order to apply these two equations to solve for A_n and B_n, the primary field E_0 due to the current-carrying wire at O' must be represented with reference to the origin O as shown in Figure 1. The following additional theorem for Bessel Functions given by Watson,[5] p. 361, accomplishes this:

$$K_0(\gamma_1\bar{\rho}) = \sum_{n=0}^{\infty} \epsilon_n^* K_n(\gamma_1\rho_0) I_n(\gamma_1\rho) \cos n(\phi - \phi_0) \quad \text{for} \quad \rho < \rho_0 \tag{6}$$

where

$$\epsilon_n^* = 1 \quad \text{for} \quad n = 0$$

and

$$\epsilon_n^* = 2 \quad \text{for} \quad n \geqq 1.$$

Employing this result the fields outside and inside the cylinder are written

$$E_1 = -\frac{i\mu\omega I}{2\pi} \sum_{n=0}^{\infty} \epsilon_n^* K_n(\gamma_1\rho_0) I_n(\gamma_1\rho) \cos n(\phi - \phi_0) + \sum_{n=0}^{\infty} A_n K_n(\gamma_1\rho) \cos n(\phi - \phi_0) \quad \text{for} \quad \rho_0 > \rho \geqq a \tag{7}$$

and

$$E_2 = \sum_{n=0}^{\infty} B_n I_n(\gamma_2\rho) \cos n(\phi - \phi_0) \quad \text{for} \quad \rho \leqq a. \tag{8}$$

The boundary conditions can now be applied directly to obtain the following two linear simultaneous equations for the solution of A_n and B_n:

$$-\frac{i\mu_1\omega I}{2\pi} \epsilon_n^* K_n(\gamma_1\rho_0) I_n(\gamma_1 a) + A_n K_n(\gamma_1 a) = B_n I_n(\gamma_2 a) \tag{9}$$

and

$$-\frac{i\mu_1\omega I}{2\pi} \epsilon_n^* K_n(\gamma_1\rho_0)) I_n'(\gamma_1 a) \quad \frac{\gamma_1}{\mu_1} + A_n K_n'(\gamma_1 a) \frac{\gamma_1}{\mu_1} = B_n I_n'(\gamma_2 a) \frac{\gamma_2}{\mu_2}$$

where the prime on the Bessel function indicates a derivative with respect to its argument. When the expression for A_n is inserted in equation 7 the expression for the field anywhere outside the cylinder is given by:

$$E_1 = -\frac{i\mu_1\omega I}{2\pi} \sum_{0}^{\infty} \epsilon_n^* q_n \frac{I_n(\gamma_1 a) K_n(\gamma_1\rho_0) K_n(\gamma_1\rho)}{K_n(\gamma_1 a)} \cos n(\phi - \phi_0) + E_0, \tag{10}$$

where

$$q_n = \frac{\frac{1}{\eta_1}\frac{I_n'(\gamma_1 a)}{I_n(\gamma_1 a)} - \frac{1}{\eta_2}\frac{I_n'(\gamma_2 a)}{I_n(\gamma_2 a)}}{-\frac{1}{\eta_1}\frac{K_n'(\gamma_1 a)}{K_n(\gamma_1 a)} + \frac{1}{\eta_2}\frac{I_n'(\gamma_2 a)}{I_n(\gamma_{\ 2} a)}}$$

and

$$\eta_1 = \left(\frac{i\mu_1\omega}{\sigma_1 + i\omega\epsilon_1}\right)^{1/2}, \qquad \eta_2 = \left(\frac{i\mu_2\omega}{\sigma_2 + i\omega\epsilon_2}\right)^{1/2}.$$

The factor q_n in the above expression can be interpreted as a reflection factor which determines the amplitude and phase of the secondary cylindrical waves of order n as they are reflected from the surface of the cylinder. As the conductivity of the material in the cylinder approaches infinity the factor q_n approaches -1; for the limiting case when the cylinder has identical electrical properties to the exterior region, the factor approaches zero.

The above general expression for E_1 is quite rigorous and any arbitrary value of conductivity, dielectric constant, or permeability may be assigned to the two regions inside or outside the cylinder. For measurements in geophysical exploration the conductivity σ_1 of the medium exterior to the conducting ore zone may be relatively small. If the magnitude of the quantity $\gamma_1 a$ is much less than one, the Bessel functions with that argument may be replaced by much simpler expressions. These are well known from the theory of Bessel functions and are listed for convenience here:

$$\begin{aligned}
&I_n(\alpha) \simeq \frac{\alpha^n}{n!2^n} && \text{for} \quad n \geqq 1, \\
&K_n(\alpha) \simeq \frac{n-1!2^{n-1}}{\alpha^n} && \text{for} \quad n \geqq 1, \\
&I_0(\alpha) \simeq 1, \qquad K_0(\alpha) \simeq -(\log \alpha + .116) && \\
&\frac{I_n'(\alpha)}{I_n(\alpha)} \simeq \frac{n}{\alpha}, \quad \text{and} \quad \frac{K_n'(\alpha)}{K_n(\alpha)} \simeq -\frac{n}{\alpha} &&
\end{aligned} \tag{11}$$

where α is the argument of the Bessel function and its magnitude is much less than one.

When the outer medium has a poor conductivity the expression for the electric field E_1 outside is then given by

$$E_1 = E_0 - \frac{i\mu_1\omega I}{2\pi}\sum_1^\infty q_n \frac{a^{2n}}{\rho_0{}^n\rho^n \cdot n}\cos n(\phi - \phi_0), \tag{12}$$

where

$$E_0 = -\frac{i\mu_1\omega I}{2\pi}(\log \bar{\rho} + 0.116)$$

and where the reflection coefficient is now given by

$$q_n = \frac{\mu_2/\mu_1 - \gamma_2 a I_n'(\gamma_2 a)/I_n(\gamma_2 a)}{\mu_2/\mu_1 + \gamma_2 a I_n'(\gamma_2 a)/I_n(\gamma_2 a)}. \tag{13}$$

The following relation between Bessel functions given by Watson,[5] p. 79 is now employed.

$$\alpha I_n'(\alpha) = \alpha I_{n-1}(\alpha) - n I_n(\alpha).$$

The expression for q_n can then be compactly written as follows:

$$q_n = \frac{(k+n)I_n(\gamma_2 a) - (\gamma_2 a)I_{n-1}(\gamma_2 a)}{(k-n)I_n(\gamma_2 a) + (\gamma_2 a)I_{n-1}(\gamma_2 a)} \tag{14}$$

where k is the magnetic permeability contrast given by

$$k = \mu_2/\mu_1.$$

The arguments of the Bessel functions are still generally complex; however, the form of the parameter $\gamma_2 a$ is somewhat simplified if displacement currents within the cylinder are neglected. That is the following approximation is made:

$$\gamma_2 a = [i\mu_2\omega(\sigma_2 + i\epsilon_2\omega)]^{1/2} a \simeq (i\mu_2\omega\sigma_2)^{1/2} a \tag{15}$$

where $\sigma_2 \gg \epsilon_2\omega$. This is always justified in mineral materials when the operating frequency is less than 100 kilocycles. The arguments of the Bessel functions are then proportional to $(i)^{1/2}$ and the functions are tabulated by MacGlachlan[6] and others.

The magnetic field components $H_{1\rho}$ and $H_{1\phi}$ in the region outside the cylinder can be found directly from Maxwell's equations:

$$H_{1\rho} = -\frac{1}{i\mu_1\omega\rho}\frac{\partial E_1}{\partial \phi} = \frac{I}{2\pi}\sum_1^\infty q_n \frac{a^{2n}}{\rho_0{}^n \cdot \rho^{n+1}} \sin n(\phi - \phi_0) + H_{0\rho} \tag{66}$$

and

$$H_{1\phi} = \frac{1}{i\mu_1\omega}\frac{\partial E_1}{\partial \rho} = \frac{I}{2\pi}\sum_1^\infty q_n \frac{a^{2n}}{\rho_0{}^n \cdot \rho^{n+1}} \cos n(\phi - \phi_0) + H_{0\rho}, \tag{17}$$

where $H_{0\rho}$ and $H_{0\rho}$ are the components of the primary magnetic field of the cable in the ρ and the ϕ directions respectively.

In many cases only the first term in the above series is significant if the ratio a/ρ or a/ρ_0 is much less than one. The expression for the fields can be written:

$$H_{1\rho} - H_{0\rho} \simeq \frac{I}{2\pi\rho_0} q_1 \frac{a^2}{\rho^2} \sin(\phi - \phi_0) \tag{18}$$

and

$$H_{1\phi} - H_{0\phi} \simeq \frac{I}{2\pi\rho_0} q_1 \frac{a^2}{\rho^2} \cos(\phi - \phi_0). \tag{19}$$

The factor q_1 is now given by

$$q_1 = \frac{(k+1)I_1(i^{1/2}m) - i^{1/2}mI_0(i^{1/2}m)}{(k-1)I_1(i^{1/2}m) + i^{1/2}mI_0(i^{1/2}m)}, \tag{20}$$

where

$$m = (\sigma_2\mu\omega)^{1/2}a.$$

This quantity has a real and imaginary part and is written as follows:

$$q_1 = -(u_1 + iv_1).$$

The quantities u_1 and v_1 are plotted in Figure 2 as a function of m.

It may be desirable to express the magnetic fields in terms of a vertical component H_{1y} and a horizontal component H_{1x} when the surface of the earth is considered to be a plane parallel to the (xz) plane as shown in Figure 1. These components are related simply to the $H_{1\rho}$ and $H_{1\rho}$ components as follows:

$$H_{1x} = H_{1\rho}\cos\phi + H_{1\phi}\sin\phi \tag{21}$$

and

$$H_{1y} = H_{1\rho}\sin\phi - H_{1\phi}\cos\phi. \tag{22}$$

SIGNIFICANCE OF RESULTS

The rigorous solution for the infinite current carrying wire running parallel to the conducting cylinder gives the exact solution for the secondary fields. This assumed that the medium exterior to the cylinder is infinite and has homogeneous electrical properties. When the frequency is relatively lower such that the quantities $|\gamma_1 a|$, $|\gamma_1\rho|$, and $|\gamma_1\rho_0|$ are much less than one the external medium behaves as it were an insulator in the presence of a current-carrying ungrounded wire. The parameter $|\gamma_2 a|$ on the other hand involves the conductivity of the material of the cylinder which in general may have any value from values much less than one to values much greater than one. For example if the exterior medium were barren rock the conductivity σ_1 may be 10^{-3} mhos per meter, with radius a equal to 10 meters and the angular frequency equal to 10^3 then

$$|\gamma_1 a| \simeq 10^{-2}.$$

On the other hand the ore zone conductivity σ_2 may be as high as 10^2 mhos per meter for massive sulphide regions whence

$$|\gamma_2 a| = m \simeq 3.$$

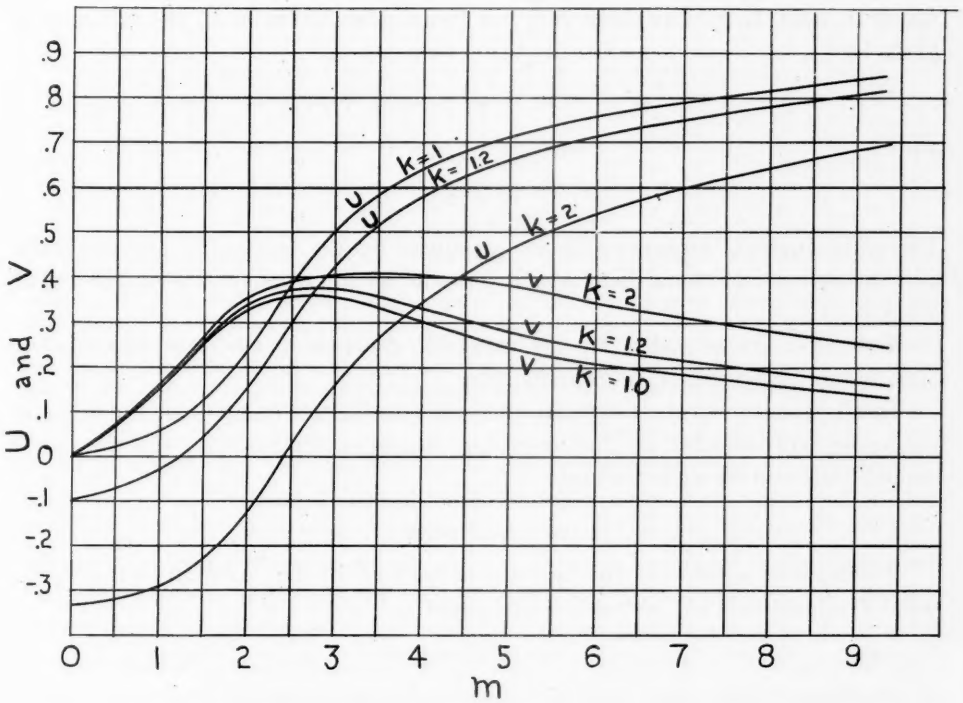

FIG. 2. The behavior of the in phase and the quadrature components u_1 and v_1 respectively of the secondary magnetic field for the case when the surrounding medium has a relatively poor conductivity.

The curves of u_1 and v_1 in Figure 2 show the behavior of the in phase and the quadrative components of the secondary magnetic fields for a cylinderical conductor in the presence of a parallel current-carrying cable when the above mentioned approximations are valid. When $k=1$ to indicate the case of no magnetic property contrast between the media the secondary magnetic fields are due only to induced eddy currents that flow within the cylinder. At lower frequencies the quadrature component denoted by v_1 predominates. At higher frequencies where m becomes larger the secondary field contains a large component which is in phase with the current in the cable. At very high frequencies the induced currents flow entirely on the surface of the cylinder and the in phase component predominates.

The curves are modified somewhat when the magnetic permeability of the cylinder material becomes greater than the exterior medium. A 20 percent increase is not uncommon (i.e., $k=1.2$) for massive ore bodies. The in phase and quadrature components for this case are shown plotted in Figure 2. At very low frequencies the secondary fields have an anti-phase component that predominates. In this case the magnetic contrast causes a concentration of magnetic flux which gives rise to a secondary magnetic field of opposite sign to the primary

magnetic field. In fact at these very low frequencies where $m \ll 1$ the factor q_1 is given by

$$q_1 = -u_1 = \mu_2 - \mu_1/\mu_2 + \mu_1$$

and

$$v_1 = 0.$$

The eddy currents however still are produced by the oscillating primary field and set up an additional field which follows the same pattern as for the case when $k = 1$.

The curves of u_1 and v_1 for the magnetic contrast of $k = 2$ are also shown. This is considered rather an extreme case.

In all cases however, it appears that the quadrature component for $m \leqq 2$ is not appreciably affected by the presence of magnetic contrast between the cylinder material and its surroundings.

ACKNOWLEDGMENT

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4. Otto Mayr; *Electrotechnische Zeitschrift* (1925), p. 1352.
5. G. N. Watson; *Theory of Bessel Functions*, 2nd Ed. Cambridge (1944).
6. N. W. McGlachlan; *Bessel Functions for Engineers*, Oxford (1935).

SIMULTANEOUS GAMMA-RAY AND NEUTRON LOGGING*

GILBERT SWIFT†

ABSTRACT

Newly developed instrumentation for Radioactivity Well Logging is described whereby two curves, the Gamma-Ray Curve and the Neutron Curve, are made simultaneously, together with a record of the casing collar positions, on one upward passage of the logging instrument. A functional description of all of the system elements is provided, showing how the resulting log is continuously drawn in the surface vehicle on a multi-pen recorder, with consequent saving in rig-time and elimination of possible depth discrepancy between curves, which may exist where successive runs are required. The application of radioactivity logs to production problems is briefly discussed.

Since 1940, when the Gamma Ray Curve was commercially introduced, and 1942, when the Neutron Curve became available, more than 45,000 wells have been logged by these methods, using a technique whereby each curve is obtained during a separate traverse of the well. This paper describes newly developed instrumentation which performs both of these logging processes simultaneously.

A Gamma Ray Curve is produced by continuously moving a detector of gamma radiation and recording its indications as it progresses along the well bore. This curve is a graph of the intensity of natural radioactivity of the various rocks surrounding the well bore, plotted with respect to depth. It serves generally to locate the exact position and thickness of each formation and to differentiate between various types of rock material. The distinctive features of the gamma ray curve permit correlation from well to well over great distances.

The observed radioactivity is principally due to the presence in the rocks of very small amounts of the elements of the uranium series, the thorium series, and potassium. Sandstones and limestones generally contain lesser amounts of these elements than do shales and clays, and the gamma ray curve is therefore able to distinguish between these groups. The Neutron Curve supplements this identification by providing a measure of the amount of fluid present in the rocks. This curve is obtained by moving along the well a strong source of neutrons together with a gamma ray detector, thus observing the gamma rays which are liberated in the rock as it undergoes bombardment by the neutrons. The detector used in this process is sufficiently smaller and less sensitive than that used for the Gamma Ray Curve so that it provides measurements of the induced radiation without interference from the weak natural radiation.

The induced radiation is influenced principally by the amount of hydrogen in the vicinity of the instrument and this in turn is a function of the fluid content of the rocks. The response of the neutron curve to variations of fluid filled poros-

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ity is so consistent in many limestone reservoirs that porosities can be determined quantitatively from the curve. The numerical relationship between neutron curve response and and porosity is established from one or more wells where the porosities are known from core data and then applied to the neutron curves of other wells in the field.

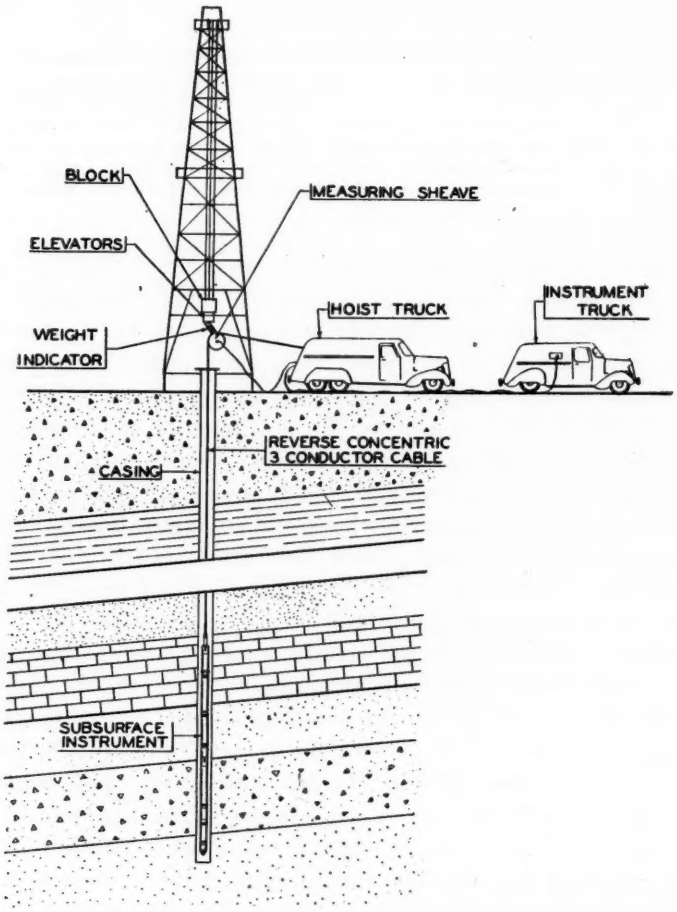


FIG. 1. Logging equipment required.

The great penetrating power of the radiations employed in both Gamma Ray and Neutron well logging enables the curves to be run in open hole or through casing and in any type of well fluid. The observed intensities are, however, quite low; and since accurate measurements of low radioactive intensities are inconsistent with high speed, the process is necessarily a time consuming one. Logging speeds which provide the necessary accuracy range from 1,200 to 3,600 feet per hour depending on locality. Two curves, made one at a time, throughout a 12,000 foot well thus take from 7 to 20 hours.

Currently, the two curves are run in more than 80 percent of the cases, and the majority of these represent new wells where drilling crews and equipment are standing idle during the logging operations. The standby cost to the well-owner is far in excess of the logging service charges in such cases, thus providing the strongest economic incentive toward reduction of the time required for logging.

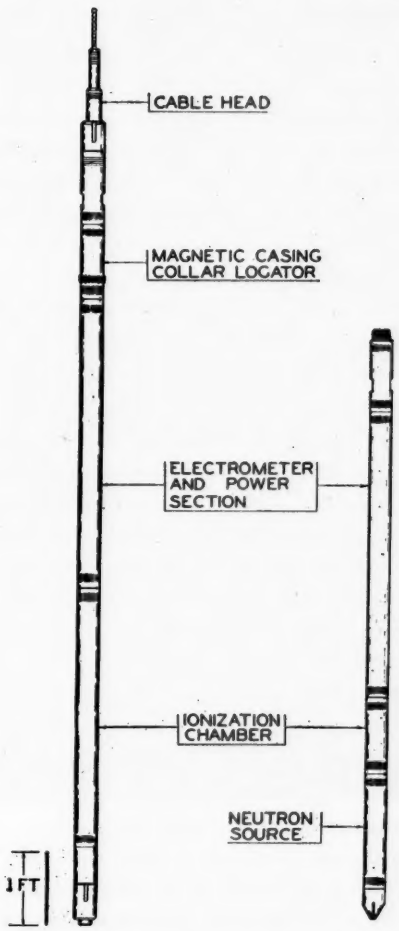


FIG. 2. Subsurface instrument.

Additionally, there is an economic incentive to enable each logging crew and equipment to serve more wells.

Under these incentives, development of the presently described equipment was undertaken with the objective of providing the same Gamma Ray and Neutron Curves simultaneously during one traverse of the well, without sacrifice of quality or accuracy of the results. This objective has been attained or surpassed. In addition, the use of a dual pen recorder permits both curves to be

drawn simultaneously on the same chart paper with the advantage that depth discrepancies between curves are eliminated. It has also been feasible to supply power from the surface to the electrical equipment in the borehole thereby eliminating the frequently depleted batteries and minimizing instrument maintenance.

The complete logging equipment comprises a hoist truck of conventional design which is also employed in perforating, an instrument truck especially designed for simultaneous radioactivity logging, and suitable subsurface instrumentation. (See Fig. 1). A minimum of two men is required for operation.

The subsurface instrument is divided into two separable sections, the lower of which produces the Neutron Curve and the upper the Gamma Ray Curve. (See Fig. 2). A magnetic casing collar locator included in this section provides an indication of each casing joint as it is passed, thus tying the radioactivity curves to permanent depth markers. Adequate shielding and separation are provided to prevent interaction of the neutron source with the gamma-ray curve detector. When coupled together these sections provide a single rigid subsurface assembly. The neutron source is a small capsule of radioactive material which produces a constant flux of fast neutrons by bombardment of alpha particles on beryllium. The radiation detectors are high-pressure ionization chambers. The remaining space in each section is occupied by electrical circuit components which are described more fully below. Coupling of the two sections is facilitated, particularly for wells with a limited overhead distance by a tong-like clamp which permits the neutron section of the instrument to be lowered into the well before picking up the gamma-ray section. After making-up the coupling, the clamp is removed and the complete instrument is lowered rapidly to the bottom of the well. The log is recorded during the upward trip, as is customary, in order to insure tension in the cable and accurate depth registration.

The subsurface instruments are transported to and from the job in the recording truck where they are stowed underneath the operator's bench. The recording apparatus is mounted in a console along the opposite-side of the vehicle. The console includes a set of operating control panels, and a modified commercial two-pen high speed electronic recorder. (See Fig. 3).

On the right the uppermost group of controls operate the various convenience and safety accessories such as lights, fans, intercommunication system, and horn. Below this is a cathode ray oscilloscope used for monitoring the logging signals. Next below is the control panel for the Gamma Ray Curve and below this a duplicate unit for the Neutron Curve. At the bottom are two power supply units for the control panels above.

The recorder is located at the upper left; a synchro system drives its chart in exact relationship to the travel of the hoist cable, at one of the standard log scales, 1, 2, or 5 inches per hundred feet. The two curve-recording pens are electronically positioned in accordance with the variations in radioactive intensity continuously throughout the logging process. The Gamma Ray Curve is

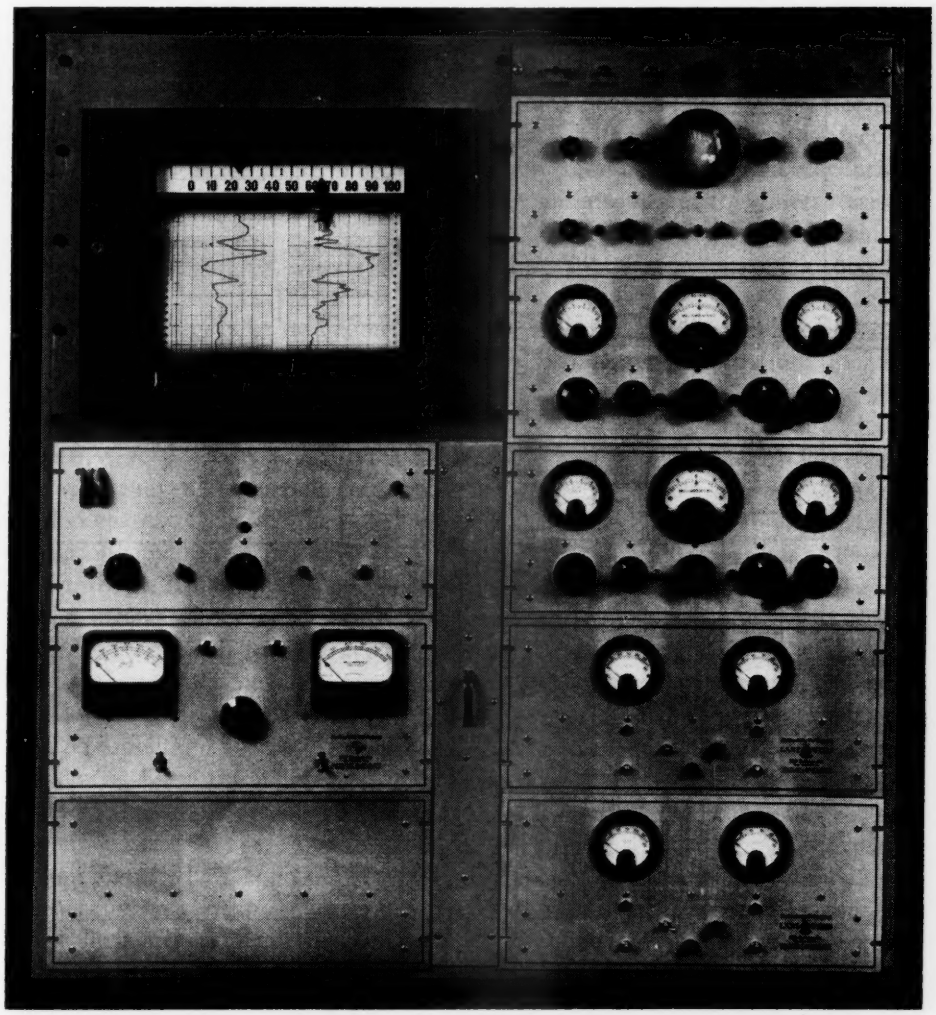


FIG. 3. Recording apparatus.

drawn at the left, while at the right the second pen draws the Neutron Curve, spaced appropriately lower on the chart to correspond with the vertical distance between the two detectors in the well. The lowest recording point is within two feet of bottom for the Neutron Curve and within 12 feet of bottom for the Gamma Ray Curve. If excessive intensity variations are encountered while recording the log, the pens are able to cross each other. In the left margin of the chart a solenoid actuated pen registers the casing joint positions. Directly below the recorder unit is a control panel which receives signals from the casing collar detector and energizes the margin pen. Below that is the unit which supplies power for operating the subsurface equipment.

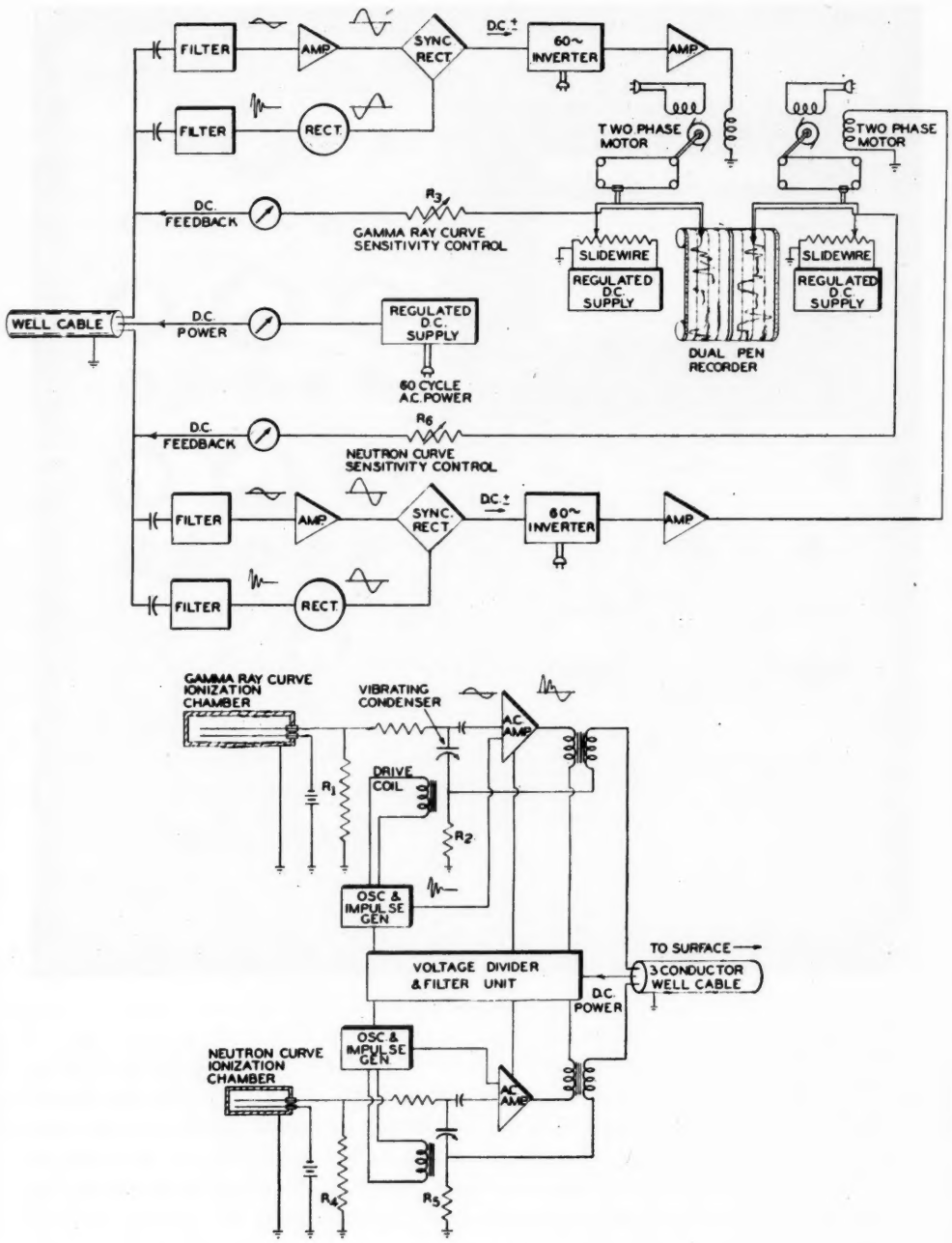


FIG. 4. Arrangement of circuit elements.

The Gamma Ray and Neutron Curves are each recorded by continuous null-balance systems which operate independently of each other, over two of the three conductors within the well-cable. The third conductor carries the necessary power to both instruments. By virtue of the null principle, the minute direct currents produced in the ionization chambers by the gamma radiation are accurately recorded at the surface, independent of wide variations in cable characteristics, vacuum tube amplification and other factors subject to change. This is achieved by the arrangement of circuit elements shown in the accompanying diagram. (See Fig. 4.)

The system may be said to begin at the ionization chamber which provides a minute direct current proportional to the incident gamma radiation. This current, usually less than 10^{-12} amperes, flows through a high value resistor R_1 to ground. The voltage appearing across R_1 is therefore a measure of the radiation intensity. R_2 is a very low value resistor, customarily 10^{-10} times as large as R_1. Then, whenever the current through R_2 is exactly 10^{10} times as great as the ionization current there will be equal voltages across the two resistors. This is the condition of balance at which the system automatically maintains itself. The current through R_2 is supplied over the well cable from a slidewire in the recorder at the surface and varies directly in proportion to the displacement of the recorder pen from left to right across the chart. Thus, in maintaining balance, the pen is concurrently moved to left or right in exact correspondence with the variations of the ionization current.

To follow the automatic functioning of the system assume that the system is in balance. Now any increase in gamma radiation will raise the potential of R_1 above that of R_2. A sensitive electrometer, of the vibrating condenser type, is connected between these two resistors and senses this unbalance. An alternating current signal, the magnitude of which corresponds to the amount of unbalance, is generated by the motion of the electrometer. This is amplified and transmitted to the surface equipment where it is employed to move the pen and correspondingly readjust the feedback current toward a new position of balance. Upon reaching balance, no potential difference exists and electrometer transmits no corrective signal to the surface. The recorder therefore stops at this new position. Instability is avoided by a feedback network within the recorder. The system characteristics are such that the speed of motion of the recorder mechanism is proportional to the magnitude of the unbalance. Its direction of motion is controlled correctly by preserving polarity and phase relationships throughout the system. It is this requirement which makes the apparatus appear more complicated than it actually is. The electrometer responds to a reversal of polarity of the unbalance by a phase reversal of its output signal. To retain this sense of direction in the surface equipment, a phase reference is required against which the electrometer output signal can be compared. This is accomplished by transmitting, over the same cable conductor, a higher frequency wave-train which is repeated continuously at the same rate as the vibration of the electrometer. This

wave-train is derived from the mechanism which drives the vibrating condenser and is therefore unalterably synchronized with it. After rectification and filtering, this wave provides a reference signal of the same frequency as the electrometer output signal but unvarying in magnitude or phase. The two signals are compared in synchronous rectifier located in the control panel and result in a direct current similar, in magnitude and polarity, to the unbalance observed by the electrometer, but at a very much higher energy level. This direct current enters the recorder unit where it is converted to alternating current by the 60-cycle chopper unit common to this class of recorder.

Here again a change of polarity of the direct current produces a phase reversal, which in turn determines the direction of rotation of the two-phase motor employed to position the pen and the slidewire arm. In this way, the recorder movement is controlled in velocity and direction so as to always reduce any unbalance to zero; increasing or decreasing the feedback current as required to achieve this condition.

The sensitivity, which may be expressed in terms of inches of pen travel for a given change in ionization current, is varied by adjusting R_3. When this resistor is relatively small, little motion is required for the needed change in feedback current; when R_3 is increased the slidewire arm and pen must travel further to produce the same current change. The value of R_3 is always large compared with the series resistance of the well cable, thus variations of the cable with temperature or due to other causes produce no appreciable effect on the system. Since R_2 is extremely small, leakage of the cable insulation becomes negligible. With a fixed value of R_3 and a constant voltage across the slidewire, the pen position is determined solely by the ionization current and the ratio of two resistors, R_1 and R_2, and is essentially independent of the performance of the remaining circuit elements.

All of these important characteristics, which have been employed in Radioactivity Well Logging since its inception, are retained in this dual equipment through the use of the separate conductors in the well cable to permit simultaneous operation of two null-balancing circuit-chains. Interaction between the two is imperceptible, even though an appreciable amount of cross-coupling for alternating currents may exist in the cable. This immunity stems from the use of the null-balance system in which the recorded information is transmitted by direct current; alternating currents are employed only for error correction purposes.

The curves obtained simultaneously with this dual equipment are in all respects equal to those made separately, while the operating time is approximately cut in half. With minor exceptions, the operation and maintenance procedures remain the same.

The author wishes to acknowledge the contributions of the technical staff of Well Surveys, Incorporated in carrying out the development of this apparatus, the staff of Engineering Products Corporation in assembling the vehicular equipment, and the managements of the Lane-Wells Company and Well Surveys, Incorporated in encouraging this undertaking.

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,573,682. W. M. Barret. Iss. 11/6/51. App. 3/17/41 and 3/24/45. Assign. Engineering Research Corp.

Means and Method for Electromagnetic-Wave Investigations. A method of electromagnetic prospecting by radiating an electromagnetic wave, receiving the waves with a receiver which is maintained at constant amplification, and observing the change in length and height of radiator required to maintain a constant intensity of received signal as the radiated frequency is varied.

U. S. No. 2,575,340. M. K. Goldstein. Iss. 11/20/51. App. 3/7/46.

Determination of Ground Constants. An electromagnetic-prospecting system in which a frequency-modulated wave is radiated in the earth and picked up by receivers located at various points, the frequency shift of the received signals being observed.

U. S. No. 2,575,349. F. W. Lee. Iss. 11/20/51. App. 1/6/49.

Geophysical Surveying. A system for electrically exploring around a borehole using one potential electrode in the hole and other potential electrodes on the surface on lines radiating from the hole, and with current electrodes on the surface equidistant from the hole.

GEOCHEMICAL PROSPECTING

U. S. No. 2,573,390. A. Blanchard. Iss. 10/30/51. App. 7/11/46. Assign. Schlumberger Well Surveying Corp.

Gas Detector. A device for detecting gas in drilling mud by passing it through a tube having an acoustic-wave transmitter on one side and an acoustic receiver on the other and measuring the output of the receiver.

U. S. No. 2,576,283. P. E. Chaney. Iss. 11/27/51. App. 7/28/44. Assign. Sun Oil Co.

Process of Separating Shale Cuttings from Drilling Mud Containing Plastering Agents. A method of separating shale cuttings from very heavy drilling mud by separating from the mud both the cuttings and plastering material, washing the cuttings from the plastering material and returning the plastering material to the mud.

U. S. No. 2,578,500. G. G. Bernard and M. Savoy. Iss. 12/11/51. App. 3/31/48. Assign. The Pure Oil Co.

Method of Studying Earth Formations Employing Carbon Disulfide as a Tracer. A method of tracing fluid flow in a secondary-recovery operation by injecting carbon disulfide with the flooding agent.

GRAVIMETRIC PROSPECTING

U. S. No. 2,570,659. C. H. Fay and R. R. Goodell. Iss. 10/9/51. App. 11/1/48. Assign. Shell Development Co.

Borehole Gravity Meter. A self-leveling gravimeter having the instrument suspended on gimbals and indicating the change in capacity of a condenser one of whose plates is suspended on a spring, the condenser plates being spherical segments whose center is at the center of suspension so as to eliminate any residual level effect.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,574,395. W. R. Jack and E. M. Brinker. Iss. 11/6/51. App. 3/18/50. Assign. William R. Jack.

Torsional Balance Device. A torsion balance having a horizontal torsion fiber with one end fastened to a torsion head and with the other end carrying a weighted cross arm and a magnetic armature which is attracted by a magnet to hold the fiber taut and introduce control.

MAGNETIC PROSPECTING

U. S. No. 2,570,870. O. H. Schmitt and J. H. Hidy. Iss. 10/9/51. App. 6/29/44. Assign. U. S. A.

Electrical Bridge Compensation System for Magnetometers. A compensated magnetic anomaly detector in which the compensating current through the flux-valve is obtained from a bridge containing variable impedance elements which are controlled from the output of the flux-valve demodulator with a time delay so that only protracted changes in field are compensated.

SEISMIC PROSPECTING

U. S. No. 2,570,707. J. O. Parr, Jr. Iss. 10/9/51. App. 8/16/48. Assign. Olive S. Petty.

Seismic Surveying. A towing line for marine seismograph operations having the geophones interposed in the line and with the geophone and a short length of adjacent cable arranged to be slightly heavier than water and the greater part of the cable between geophones made to float and support the geophones off bottom.

U. S. No. 2,572,255. R. L. Gallaway. Iss. 10/23/51. App. 1/18/50. Assign. The Texas Co.

Seismic Survey System for Submerged Areas. A towing line for marine seismograph operations having along the cable buoys with heavy chains and buoyant geophones on branch cables connected between the buoys so that the entire assembly is held submerged off bottom.

U. S. No. 2,574,477. R. L. Henson. Iss. 11/13/51. App. 9/12/45. Assign. Sun Oil Co.

Amplifying Circuit for Suppressing Surges Caused by Gain Control. An avc circuit in which the bias voltage of push-pull amplifying tubes is controlled from rectified output signal and the plate-current surge is compensated by supplying plate voltage through a tube whose grid is also controlled from the output.

U. S. No. 2,576,775. F. D. Case. Iss. 11/27/51. App. 7/31/48. Assign. Diamond Instrument Co.

Seismometer System. A three-component earthquake seismometer having a vertical and two horizontal pendulums with magnetic and air damping and capacity-type transducers feeding amplifiers and recorders.

U. S. No. 2,577,472. W. H. Lewis. Iss. 12/4/51. App. 7/14/48. Assign. The Pennsylvania Research Corp.

Circuit for Multiple Channel Recording Galvanometers. A circuit for multi-channel recording in which the galvanometers are in cathode-follower circuits and in which the channel signals and their differences are recorded.

U. S. No. 2,578,133. J. E. Hawkins. Iss. 12/11/51. App. 11/8/44. Assign. Seismograph Service Corp.

System of Seismic Recording. A system of seismograph recording in which the geophones modulate separate oscillators all of whose modulated signals are recorded on a single magnetic record which may afterward be played back and the separate geophone signals obtained for re-recording with desired mixing and filtering.

U. S. No. 2,578,877. C. L. Brownlow. Iss. 12/18/51. App. 5/16/46. Assign. Phillips Petroleum Co.

Seismograph Blaster Time Breaker Circuit. A seismograph shot-firing and time-break circuit which fires on a heavy timing line by having the blasting machine close the timing circuit to a thyra-

tron which closes a relay and applies the blasting generator current to a bridge circuit containing the cap and from which the shot moment is recorded.

WELL LOGGING

U. S. No. 2,569,625. M. R. J. Wyllie. Iss. 10/2/51. App. 3/30/50. Assign. Gulf Research & Development Co.

Method and Apparatus for Determining the Streaming-Potential Characteristics of Drilling Mud. A system for determining the streaming potential of drilling mud by lowering into the well a porous tube having electrodes inside and outside the tube and with an air chamber into which mud can flow under pressure and recording the change in electrode potential produced by the flow.

U. S. No. 2,569,867. R. G. Norelius. Iss. 10/2/51. App. 3/27/48. Assign. Lane-Wells Co.

Alternating-Current Electro-Logging. A four-electrode square-wave electric-logging system in which the potential electrodes are connected together or grounded during the current transient.

U. S. No. 2,570,111. R. W. Goble. Iss. 10/2/51. App. 11/21/47. Assign. Eastman Oil Well Survey Co.

Apparatus for Determining the Character of Fluids which are Present in Well Bores. A device for locating the level of fluid in a well and having a vacuum-tube oscillator whose grid circuit contains electrodes in contact with the well fluid and whose frequency and depth is recorded at the surface.

U. S. No. 2,571,529. A. A. Brant. Iss. 10/16/51. App. 5/3/49. Assign. Geophysical Exploration Co.

Drill Hole and Underground Resistivity Method. A method of electrically locating electrical earth inhomogeneities close to a drill hole by passing a current between electrodes equally spaced on either side of the hole and exploring the hole with potential electrodes and repeating with the current electrodes in a line at right angles to the first line.

U. S. No. 2,573,133. W. J. Greer. Iss. 10/31/51. App. 8/13/48. Assign. Halliburton Oil Well Cementing Co.

Well Logging System. A system for making a number of resistivity logs with a single-conductor cable by having the pick-up potentials modify the resistance of a tube in local oscillator circuits whose respective frequency-modulated signals are separated at the surface and indicated.

U. S. No. 2,573,137. W. J. Greer. Iss. 10/30/51. App. 4/21/50. Assign. Halliburton Oil Well Cementing Co.

Electric Well Logging System. A system for making a number of resistivity logs with a single-conductor cable by using a frequency divider multi-vibrator to change the frequency transmitted down the cable to other frequencies which are frequency modulated and transmitted to the surface.

U. S. No. 2,573,390. A. Blanchard. Iss. 10/30/51. App. 7/11/46. Assign. Schlumberger Well Surveying Corp.

Gas Detector. For abstract see GEOCHEMICAL PROSPECTING.

U. S. No. 2,573,961. P. W. Fischer. Iss. 11/6/51. App. 6/5/50. Assign. Union Oil Co. of Calif.

Low-Resistance Drilling Fluids. An oil-base mud having low electrical resistance to permit electric logging and containing alkali-metal alkali saponification products of wood rosin.

U. S. No. 2,575,173. E. A. Johnson. Iss. 11/13/51. App. 2/27/47. Assign. Standard Oil Co.

Apparatus for Wear Indicating and Logging While Drilling. A bit-wear indicator having an insulating coupling between the drill stem and the bit with the bit carrying an electrode connected to the drill stem and covered with insulation which wears off, the resistance between a ground electrode and the drill stem being observed at the surface.

U. S. No. 2,576,283. P. E. Chaney. Iss. 11/27/51. App. 7/28/44. Assign. Sun Oil Co.

Process of Separating Shale Cuttings from Drilling Mud Containing Plastering Agents. For abstract see GEOCHEMICAL PROSPECTING.

U. S. No. 2,580,182. F. Morgan, D. W. Reed, and M. Muskat. Iss. 12/25/51. App. 5/1/47. Assign. Gulf. Research and Development Co.

Subsurface Flowmeter. A well flowmeter having baffles to induce well fluid to flow through a central channel past an electrically-heated thermistor whose resistance changes are indicated at the top of the well.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE FOURTH QUARTER OF 1951

Patent No.	*Subject*	*Patent No.*	*Subject*	*Patent No.*	*Subject*
2,569,473	16	2,571,260	16	2,572,986	316
2,569,485	316	2,571,302	308	2,573,005	308
2,569,499	428	2,571,368	316	2,573,006	200
2,569,510	68	2,571,409	140	2,573,021	316
2,569,511	136, 32	2,571,422	460	2,573,035	200
2,569,625[a]	116	2,571,529[a]	116	2,573,069	308
2,569,676	16	2,571,605	460	2,573,070	316
2,569,714	428	2,571,644	392	2,573,133[a]	116
2,569,758	316	2,571,682	444	2,573,137[a]	116
2,569,796	444	2,571,745	16	2,573,168	12
2,569,816	68	2,571,776	160	2,573,279	12
2,569,817	68	2,571,838	308	2,573,285	4
2,569,818	68	2,571,863	148	2,573,286	428
2,569,867[a]	116	2,571,899	492	2,573,390[a]	252
2,569,900	380, 76	2,571,979	12	2,573,430	148
2,569,949	428	2,571,998	140	2,573,435	216
2,569,974	16	2,571,999	140	2,573,438	484
2,569,987	288	2,572,010	316	2,573,505	496
2,570,111[a]	116	2,572,014	316	2,573,596	460
2,570,203	316	2,572,025	100	2,573,626	68
2,570,235	316	2,572,041	316	2,573,649	168
2,570,251	316	2,572,043	312	2,573,682[a]	132
2,570,322	148	2,572,108	372	2,573,685	188
2,570,486	448	2,572,119	416	2,573,686	460
2,570,500	316	2,572,211	316	2,573,748	12, 224
2,570,578	484	2,572,255[a]	360	2,573,799	228
2,570,659[a]	180	2,572,313	484	2,573,823	16, 308
2,570,672	4	2,572,332	192, 520	2,573,870	168, 196
2,570,693	484	2,572,376	484	2,573,961[a]	116
2,570,707[a]	360	2,572,525	484	2,573,998	160
2,570,738	316	2,572,600	236	2,573,999	308
2,570,870[a]	232	2,572,668	316	2,574,000	308
2,570,978	484	2,572,693	496	2,574,198	148
2,571,019	484	2,572,725	312, 16	2,574,207	224
2,571,051	316	2,572,766	16	2,574,218	224
2,571,058	148	2,572,827	16	2,574,261	188
2,571,106	16	2,572,908	228	2,574,311	228
2,571,171	188	2,572,985	224	2,574,359	496

[a] Abstracted on preceding pages of this issue.

Patent No.	*Subject*	*Patent No.*	*Subject*	*Patent No.*	*Subject*
2,574,361	4	2,576,330	288	2,578,133[a]	360, 224
2,574,395[a]	476	2,576,417	428	2,578,299	68
2,574,432	412	2,576,452	16	2,578,500[a]	172
2,574,438	68	2,576,488	428	2,578,505	12
2,574,471	216	2,576,489	428	2,578,678	436
2,574,477[a]	372	2,576,512	200, 308	2,578,703	308
2,574,596	12, 436	2,576,600	308	2,578,722	140
2,574,600	4	2,576,601	308	2,578,758	316
2,574,632	308	2,576,718	508	2,578,782	224
2,574,656	16	2,576,775[a]	376	2,578,803	324
2,574,708	484, 224	2,576,929	316	2,578,809	484
2,574,717	80	2,576,963	316	2,578,866	484
2,574,795	232	2,577,061	4	2,578,869	484
2,574,830	136	2,577,066	288	2,578,877[a]	388
2,574,866	148	2,577,110	136	2,578,966	316
2,574,898	484	2,577,210	36	2,578,980	312
2,574,973	496	2,577,253	308	2,579,125	224
2,575,134	308	2,577,443	312	2,579,136	484
2,575,166	444	2,577,472[a]	160, 364	2,579,162	484
2,575,173[a]	208	2,577,502	316	2,579,225	416
2,575,331	68	2,577,520	312	2,579,334	288
2,575,339	484, 436	2,577,536	316	2,579,352	168
2,575,340[a]	132	2,577,548	412	2,579,569	484
2,575,349[a]	124	2,577,590	200	2,579,570	16
2,575,358	12	2,577,599	208, 520	2,579,629	428
2,575,492	148	2,577,625	392	2,579,632	428
2,575,711	236, 324	2,577,629	200	2,579,717	200
2,575,811	140, 228	2,577,814	416	2,579,719	200
2,575,909	12	2,577,815	416	2,579,825	168
2,575,910	12	2,577,875	444	2,579,852	324
2,575,990	372	2,577,892	228	2,579,994	308
2,575,999	484	2,577,912	16	2,580,057	200
2,576,135	16	2,577,942	16	2,580,151	316
2,576,155	436, 484	2,578,023	224	2,580,182[a]	144, 148
2,576,173	228	2,578,066	428	2,580,208	484
2,576,283[a]	252	2,578,104	200	2,580,293	196

ERRATUM

Dr. F. Gassmann, now with the Department of Physics at Purdue University, wishes to make the following correction for equation (11) of his paper "Elastic Waves through a Packing of Spheres," which appeared in the October, 1951 issue of *Geophysics* (Volume XVI, No. 4). Equation (11) for y should be

$$y = \frac{\sqrt{3}R}{6}[6N'' + (-1)^N + 1$$

instead of

$$y = \frac{\sqrt{3}R}{4}[4N'' + (-1)^N + 1]$$

as printed.

NOMOGRAMS

WEATHERING CHART

Charts of this type are extremely useful in determining the depth of the low-velocity layer from the uphole time and depth of shot, both in the field office and during actual recording operations where it may be desirable to position the shot at or near this interface.

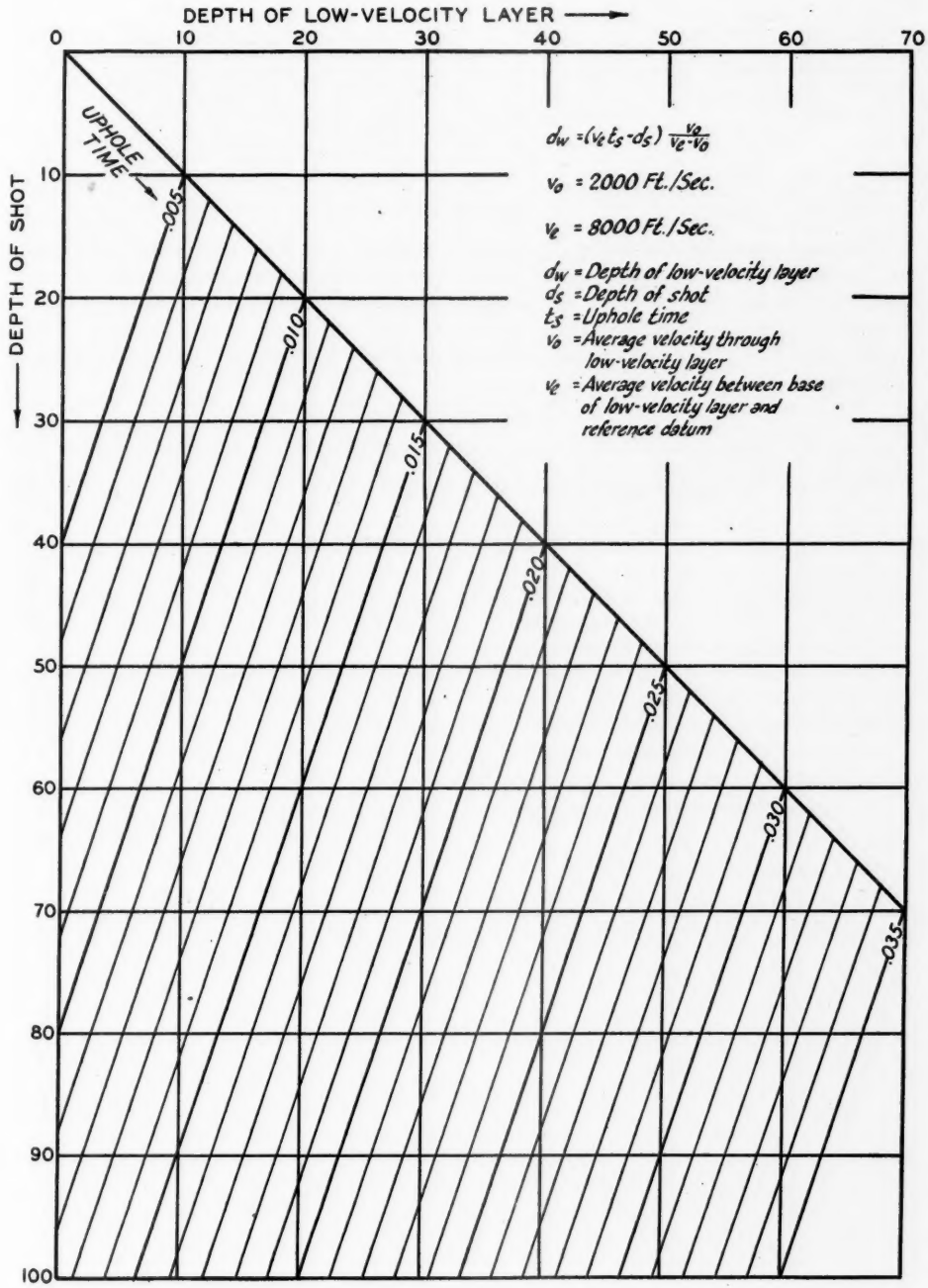
The chart is based on the formula:

$$d_w = (v_s t_s - d_s) \frac{v_0}{v_s - v_0}.$$

Different charts are required whenever the velocities vary, but are extremely simple to construct.

The thickness of the low-velocity layer may be read on the abscissa at the intersection of the proper uphole time with equivalent depth of shot. Uphole times falling above the base line are indicative of the shot being fired in the weathering.

Seismograph Service Corporation
R. W. MOSSMAN


DEPTH OF LOW-VELOCITY LAYER
0
10
20
30
40
50
60
70
DEPTH OF SHOT
10
20
30
40
50
60
70
80
90
100
UPHOLE TIME
.005
.010
.015
.020
.025
.030
.035
$d_w = (v_e t_s - d_s) \frac{v_o}{v_e - v_o}$
v_o = 2000 Ft./Sec.
v_e = 8000 Ft./Sec.
d_w = Depth of low-velocity layer
d_s = Depth of shot
t_s = Uphole time
v_o = Average velocity through low-velocity layer
v_e = Average velocity between base of low-velocity layer and reference datum

DIP CHART

This chart is used for determining dip, depth, and displacement of the shot point depth point in areas in which the inherent velocity assumptions, as shown on the chart, are applicable. The principal deterrent to the use of such charts is the extremely laborious and lengthy drafting involved in their construction.

The isotime lines ($\frac{1}{2}\, t_0$) represent curves of equal travel time from the shot point and are based on the formulae:

$$r = m \sinh t_k$$
$$z_0 = m(\cosh t_k - 1).$$

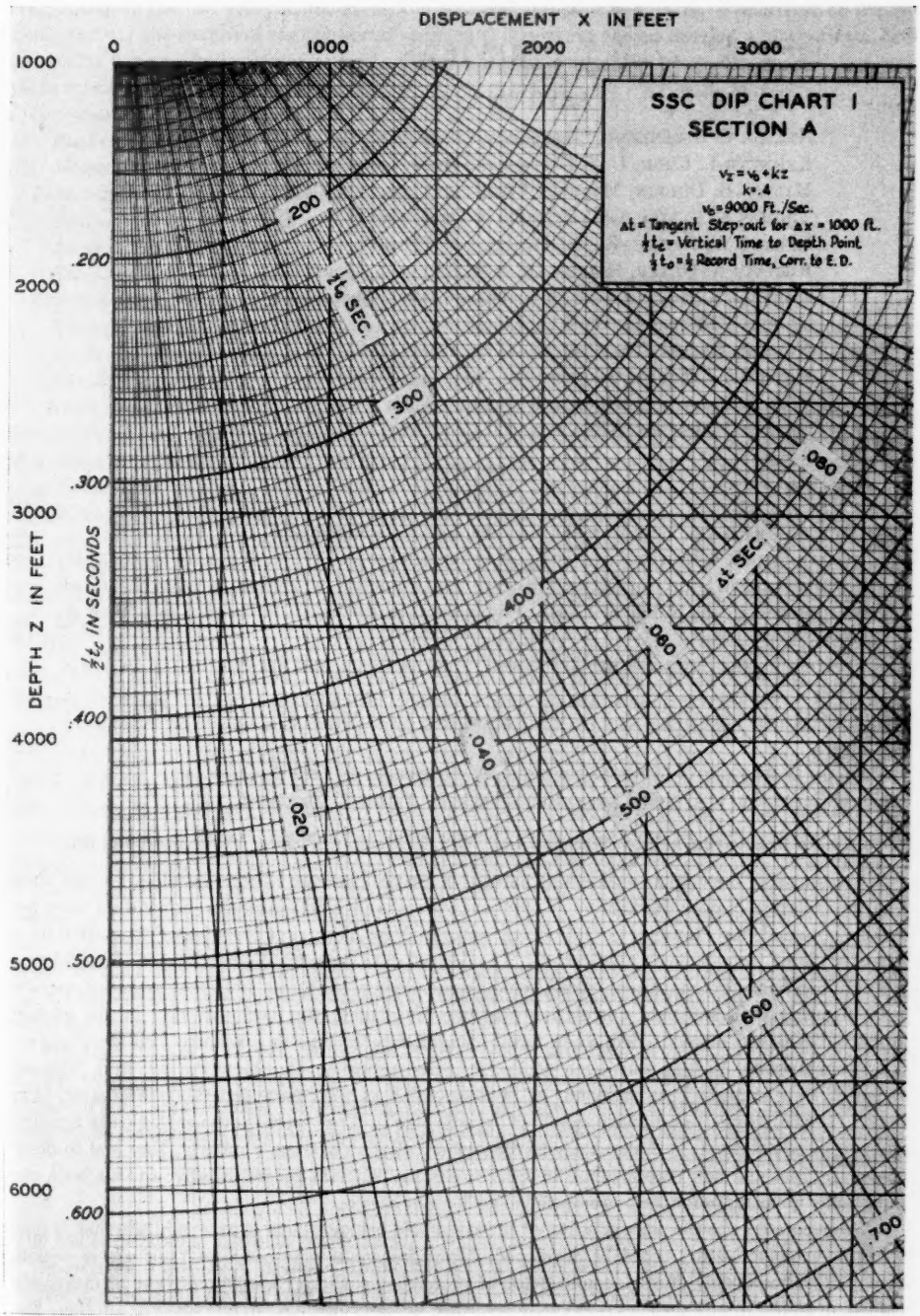
The curved ray trajectories are based on the formula:

$$\left(z + \frac{v_0}{k}\right)^2 + (x - c_1)^2 = c_3$$

where c_1 and c_3 are constants of integration. The formula reveals that if the velocity increases linearly with depth, i.e., $v_z = v_0 + kz$, the trajectories are segments of great circles whose centers are located on a line at a distance $m = v_0/k$ above the surface.

In use, the Δt obtained from the stepout over a 1,000-foot distance of the tangent drawn at the shot point to the recorded reflection times corrected for weathering and elevation is read on the appropriate trajectory at its intersection with the isotime curve representative of one-half the shot point reflection time. The displacement x and depth z and equivalent vertical time $\frac{1}{2}\, t_0$ may then be read on the superimposed rectangular coordinates. The angle of dip α may be obtained with a protractor laid tangent to the isotime line by reading the angle made with the horizontal coordinate.

Seismograph Service Corporation
A. J. BARTHELMES


DISPLACEMENT X IN FEET
0
1000
2000
3000
1000
2000
3000
4000
5000
6000
DEPTH Z IN FEET
½t_c IN SECONDS
.200
.300
.400
.500
.600
SSC DIP CHART 1
SECTION A
v_z = v_0 + kz
k = .4
v_0 = 9000 Ft./Sec.
Δt = Tangent Step-out for Δx = 1000 ft.
½t_c = Vertical Time to Depth Point.
½t_0 = ½ Record Time, Corr. to E.D.
200
¼ SEC.
300
080
4t SEC.
400
060
040
500
020
600
700

REVIEWS

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North American Geosynclines, by Marshall Kay, G.S.A. Memoir 48, New York, 1951, 143 pp.

Professor Kay devoted a considerable number of years—closer to twenty than ten, I would think—to the collating of data descriptive of sedimentary rocks in North America. Some data were personally obtained, for example, in Ordovician rocks in New York; but the greater amount were of necessity culled from geologic publications. The desired data included descriptions of chemical composition, mechanical composition, paleontologic assemblages, thickness and areal extent of member beds, together with sufficient correlative evidence for placing the data correctly in the geologic time scale. Kay was forced to define new terms for such data in order to systemize their recording and their comparisons. In this way such rock-descriptive terms as "argillicalcilutite" and "calcisilicarenite" were coined. They were not as pronounceable as their more general counterparts, "limy shale" (? "shaly lime") and "limy sand" (? "sandy lime"). They were, however, logically arranged and specifically defined, both necessary to the proper collation of data. Similarly, Kay had to design new map types and new map symbols in order to arrange his data geographically, and his book contains many novel maps for the presentation of geologic evidence.

The next step was the close scrutiny of the assembled geologic facts to ascertain whether or not a scientific geologic history could be developed. Many instances were noted of "surfaces of regional extent subsiding deeply during accumulation of succeeding surficial rocks," and these instances concluded, of course, many surfaces previously described as "geosynclinal" in one sense or another. Kay, however, adhering strictly to the preceding quotation as his definition of a geosyncline, found several definitely distinguishable types of geosynclines. There were distinguishable by (1) their geographic

relationship to the non-geosynclinal areas, the "craton" or stable area (area of relatively no deposition), and (2) the nature of the contained sediments. Kay again had to develop a new series of definitions for the geosynclinal types as in the case of the rock-descriptive terms. He resorted to Greek prefixes and several tongue-twisters resulted, to wit:*

Orthogeosynclines; long, narrow belts between cratons.

Eugeosynclines; belts of active volcanism and rapid subsidence.

Miogeosynclines; non-volcanic belts.

Intracratonal geosynclines; lie within cratons.

Exogeosynclines; sediments include some from highlands in orthogeosynclinal belts.

Autogeosynclines; elliptical in form, no complementary highlands.

Zeugogeosynclines; sediments from cratonal highlands.

Excratonal geosynclines;* in consolidated, relatively immobile, orthogeosynclinal belts.

Epieugeosynclines; actually eugeosynclines of less magnitude, lie in older eugeosynclinal belts.

Taphrogeosynclines; characterized by high-angle, block-faulting with concomitant deposition.

Paraliageosynclines; deep subsidence along present continental margins.

Kay's geosynclinal nomenclature often occasions derisive criticism because of his non-anglican constructions. Such criticisms are superficial by their own nature and only serve to obscure the results of a singular attempt to investigate scientifically accumulated geologic data. Kay's results are actually universal in scope, relating to the very origin of our planets and continents, which, by the way, is discussed in final pages of the book. The results, moreover, are of vital importance to the petroleum geologist and geophysicist. The orderly arrangement of the three fundamental areas, craton—miogeosyncline—eugeosyncline, and their synthesized depositional and structural histories enable us to make useful general predictions of geologic and geophysical conditions in unknown or little known areas.

The volume is truly one of the few that deal with fundamental geology in a manner that is essential to the professional geologist and geophysicist. It is not, however, pleasant reading. The material appears fragmentary to the reviewer, probably from having thoroughly studied it beforehand under Professor Kay. The style is uneven, even telegraphic, as though the author had been instructed to use an absolute minimal number of words. The organization of the book as a whole does not do justice to the material because of somewhat random development. Kay might have endeavored to start at the craton and progress outward toward the ocean basins. He even states that "stratigraphic evidence supports a theory that continents have grown interruptedly by reduction of oceanic areas through an intermediate 'island arc' stage." That could have been one of several good basic concepts for the organization of the material. Similarly the development of individual ideas is sometimes beclouded by the presentation. For example, Misch is quoted on p. 98, "granitization is restricted to them" (i.e., eugeosynclinal strips). In the next section, p. 99, Kay states that "masses of granite . . . extend far back into the hedreocraton," and he continues by explicitly refuting Misch in the very next sentence. Such development is disturbing even though we recognize that Misch's ideas were included for the sake of completeness.

The contents are, however, indispensable regardless of style and development. The basic ideas that evolve are well founded and for the most part incontroversial. This reviewer thought, for example, that the separation of the so-called "excratonal" types from the orthogeosynclinal group is questionable inasmuch as they may equally be construed as phases of orthogeosynclinal development.

NELSON C. STEENLAND

"The Primary Seismic Disturbance in Shale," by Norman Ricker and W. A. Sorge, *Bulletin of the Seismological Society of America*, University of California Press, Berkeley, California, Vol. 41, No. 3, July, 1951, pp. 191–204.

* The brief definitions and the word "excratonal" are not after Kay but are fabricated by the reviewer to facilitate the tabulation.

This is a succinct and well illustrated account of the results of field studies of the primary seismic disturbance at distances of 100 to 800 ft from the shot point. The formation (the Pierre shale in Eastern Colorado) is almost homogeneous and isotropic. These studies were carried out by means of an elaborate flat-response, distortion-free system with geophones peaking at $3\frac{1}{2}$ cps at $\frac{1}{4}$ of critical damping. Times were measured to 10^{-4} sec.

The chief merit of this paper is that it presents clearly and concisely some features of the primary disturbance that are not well understood and are, as a rule, inadequately described in the literature. It is shown that:

(1) The decrease of amplitude of velocity with distance follows the $R^{-5/2}$ law.
(2) The pulse width (apparent duration of the first half cycle) increases with distance as $R^{1/2}$.
(3) The seismic punch (extrapolated amplitude of particle velocity at 1 sec travel time) is a function of depth of shot. Maximum punch is usually obtained for a shot depth of 100 ft (25 to 50 ft beneath the base of the weathered layer). In one case at least, the depth is 10 to 20 ft greater, and in several cases secondary maxima are obtained at depths of 150 to 200 ft.

The latter feature is of considerable importance in seismic prospecting. An explanation for it may be found on the basis of the usual theory of elastic waves which ignores inhomogeneity, anisotropy, damping, and large displacements. More elaborate treatments involving one or several of these neglected properties should be necessary to account for the $R^{-5/2}$ law of amplitude decrease and the $R^{1/2}$ law of pulse widening.

This article is thus a striking illustration of the insufficiencies of the usual theories of elastic wave generation and propagation within the Earth.

IVAN TOLSTOY

"An Electromechanical Source of Elastic Waves in the Ground," by F. F. Evison, *Proceedings of the Physical Society, B, Vol. LXIV*, 1951, pp. 311–322.

This paper is of special interest to the reviewer since it is concerned with the generation of single frequency wave trains in the ground; Howell, Kean, and Thompson published a paper in 1940* along these lines. However, Evison has established coupling with a chalk of fairly high rigidity whereas we coupled to the water table near the surface. He shows oscillograms made over short time intervals with pulses of 300 and 600 cycles per second, the patterns showing various types of waves and paths. The geological significance of these records is to be discussed in another paper. Although the efficiency of his shaker appears to be low compared with the computed efficiency of a dynamite explosion, he feels that the purity of the wave form offers compensating advantages. The paper contains a thorough analysis of the equipment as coupled with the ground.

LYNN G. HOWELL

"A New Approach to the Study of Elastic Propagation in Rocks," by F. F. Evison, *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, Vol. 6, No. 4 (1951), pp. 209–221.

The "new approach" referred to in this paper involves the use of mechanical rather than explosive sources of elastic waves, also the placing of such sources in mines to avoid coupling difficulties of the type that are usually encountered with weathered surface materials. Although many experiments have been performed to study the propagation of waves generated by oscillators and shakers, this is the first instance in which such investigations have been performed beneath the earth's surface.

The apparatus employed in this work was described in detail in an earlier publication† and this paper is concerned primarily with the results obtained at two test locations, both of which are underground quarries. At each location, geological structure is well known and the data serve to evaluate the techniques used in the experiments.

* L. G., Howell, C. H. Kean, and R. R. Thompson, "Propagation of Elastic Waves in the Earth," *Geophysics*, Vol. 5, pp. 1–14, 1940.

† See preceding review.

The source of energy was a Fessenden oscillator, weighing 600 pounds, which vibrated at frequencies up to 1,000 cps. This was anchored by bolts cemented into the floor of the mine. Pulses were generated with a sudden onset, constant level of envelope, and time duration of 20 milliseconds. The frequencies of the oscillations within the pulses could be adjusted at 300, 600 or 1,000 cps. The signals were received with an inertia-operated Rochelle-salt crystal microphone clamped to the rock and were recorded on an oscillograph screen. It was generally observed that the received pulse was five to ten times as long as the radiated pulse, with an irregular envelope. This, by the way, is in contrast to the results observed by Howell, Kean, and Thompson,* who in similar experiments on the earth's surface observed very little change in pulse duration or envelope shape over a transmission distance of 1,200 ft.

Various peaks in the envelope were correlated on records made within the mine at increasing source-detector distances, and each peak was associated with a specific mechanism of propagation, e.g., direct compressional wave, direct shear wave, as well as eight events assumed to be compressional shear or composite reflections from interfaces below the floor of the mine. It is difficult for the reviewer to see how the times of such peaks could be measured with confidence to the nearest millisecond and used for velocity specification when the input pulses were 10 milliseconds long.

An effort was made to relate amplitudes of the various reflections with values predicted theoretically by Knott and by Muskat and Meres. The conclusions drawn from this comparison are not very convincing. Attenuations of compressional and shear waves in chalk were determined from observed amplitude decrements and these may constitute the most useful aspect of the results.

Although Evison's experiments are interesting and suggest some new applications of seismology to mining and engineering studies, it is not felt that his approach is as new and revolutionary as the reader might be led to expect from the paper's over-enthusiastic introduction. Although explosive sources have certain limitations in fundamental studies of seismic wave propagation, there are few items of information obtainable from mechanical vibrators which can not be secured equally well and more conveniently from properly prepared explosive charges with multi-channel recording. The recent literature gives numerous examples in which the direction, reflection, refraction, and absorption of sound have been studied to advantage with conventional dynamite sources.

MILTON B. DOBRIN

"Crustal Structure and Surface-Wave Dispersion," by Maurice Ewing and Frank Press, *Bulletin of the Seismological Society of America*, University of California Press, Berkeley, California, Vol. 40, 1950, pp. 271–280.

Seismic refraction work by the authors and associates (*Bull. Seism. Soc. of Am.* 40: 1950, 233–242) in the North Atlantic showed 1.37 km of sediments overlying a layer having a compressional wave velocity of 7.58 km/sec. This velocity indicates an ultrabasic rock underlying the sediments in contrast to the usual assumption of a granitic layer. The velocity is also somewhat higher than has been deduced by past writers from studies of travel time and dispersion.

The authors assume that since the velocity in the sediments differs but slightly from that in water, the two may be lumped together and then the Rayleigh wave dispersion curves for bottoms of granite and of basic rocks may be worked out. The theoretical curve for the basic rock is then shown to provide an excellent fit to the observed dispersion in several earthquakes. In particular a good fit is obtained over a much wider range than heretofore. This indicates a shear velocity of 4.45 km/sec depending upon the particular value of Poisson's ratio used.

Thus by taking account of the overlying water, the apparent difference in character between the Atlantic and Pacific oceans vanishes. The same shear velocity 4.45 km/sec is found for both. This result is also in excellent agreement with deductions from seismic profiling in the Atlantic ocean.

DARRELL S. HUGHES

"Results of Seismic Investigations in the Peissenberg Coal Mine," by H. Reich, *Erdöl und Kohle*, Vol. 4, No. 9, Sept. 1951, pp. 358–543.

The primary objective of this refraction survey, conducted at a depth of 650 meters, was to determine the elastic properties of a series of marls and sandstones having an average dip of about 9 degrees. Average velocities of 3,200 and 3,600 meters per second were observed for longitudinal waves in the Molasse marl stone and Promberger sandstone, respectively. The investigators were aware of the effect of anisotropy as a factor in governing velocities. However, the plan of the mine did not permit this phase of the experiment to be conducted.

The average velocity for the transverse wave through the marls and sandstones was also determined, and values of 1,800 and 2,150 meters respectively were observed. The formations in this mine are cut by several faults, and one interesting fact resulting from these experiments is that the longitudinal wave velocity increased appreciably for the two different formations as the fault zones were approached. In these areas minimum longitudinal velocities for marl and sandstones of 3,560 and 4,700 meters respectively were observed. The author attributes this increase in velocity to the fact that the fault is old geologically and any breaks in the rocks have been cemented with calcareous material.

The pertinent travel time curves are illustrated, together with a plan of the mine level at which the experiments were conducted, and the stratigraphic section. Details of the recording equipment used are also given. Experiments of this type, together with laboratory investigations of seismic wave velocities in rocks (such as those of Birch and Hughes), and statistical studies of field data (such as Faust, Weatherby, and West) should do much to increase our knowledge of the lithologic and geologic factors affecting the seismic characteristics of rocks; thereby helping to solve some of the problems associated with the interpretation of refraction and reflection seismic surveys.

RICHARD A. GEYER

"Sondage du Glacier par la Méthode Sismique," (Subsurface Glacier Investigations: Seismic Sound-Soundings), by A. Süsstrunk, La Houille Blanche Número Spécial A, Mai, 1951.

This paper discusses descriptively the modern application of the seismic technique to the study of European glaciers.

The reflection method predominates and standard equipment is a typical U. S. portable prospecting rig. Geophones are set in a rectangular array for depth and dip determinations of reflections not in the vertical plane of the shot line, and the ratio of shot distance to depth is critical. Two sample records are reproduced on which the direct longitudinal and transverse waves, and reflected longitudinal waves are identified. Surface waves are neither identified on the records nor discussed in the text and one cannot help but wish that the author had added a few lines on this subject. Depth values are considered accurate to ± 3 percent. The method is ineffective for ice thicknesses less than 50–100 meters because of deterioration of the ice and poor contact of the ice with the underlying rock.

A complete list and bibliography of European glaciers explored by the seismic technique is presented, and three examples are described briefly. A seismic investigation of the Glacier du Gorner in Valais, Switzerland, in 1948 gave depths to bedrock that agreed well with 15 borings for the first verification of the method in Switzerland. In 1949, on the Glacier of Mont-Collon in Valais, a weak reflecting horizon above and approximately parallel to the ice-bedrock interface was detected and led to the postulation of an intermediate moraine. Evidence for this is good at the foot of the glacier where 4 to 10 meters of alluvium cover older inactive ice and further investigation of the problem is underway. A third investigation on the Mer de Glace on Mont Blanc in 1950 gave less satisfactory results because of difficulty in obtaining the correct longitudinal wave velocity, which is apparently a function of depth.

JACK E. OLIVER
Lamont Geological Observatory
(Columbia University)

"Regional Correction of Gravity Data," by Raoul Vajk, *Geofisica Pura & Applicata*, Vol. XIX, Fasc. 3–4, Milano, Italy, 1951, pp. 129–143.

There are two basic tenets in Vajk's presentation of the problem of regional corrections, namely,

(1) The definition of the "regional effect" as "those gravity effects . . . which are of comparatively large extent, have the characteristics of gravity effects of deep seated masses, and in which—for some reason or other—we are not interested,"

and

(2) "no unique determination of the regional effect is possible and no mechanical method for its removal can be found."

Both points are generally acceptable and useful within their own limits so it is of interest to follow Vajk's development of his thesis.

First of all, methods of determining the regional are discussed. These may be summarized by saying that they consist of constructing a comparatively smooth gravity map. The smooth map may be derived from the construction of numerous smooth profiles or simply by smoothing the contours on the map itself. Known geologic conditions are considered whenever possible in order to develop the most correct regional map. The final map is admittedly the result of the personal judgment of the interpreter. The residual anomalies, or the desirable anomalies, are found by subtracting the regional map from the original map, thereby leaving the residual anomalies in their original units of gravitational intensity. (The discussion in the article itself is unnecessarily elaborate because of the use of torsion-balance nomenclature. Simple and common procedures are made to appear complex, detracting from the readability of the paper.)

Vajk concludes by describing the disadvantages of the mechanical or grid methods of determining residual anomalies. His three criticisms are:

(1) "the computed 'regional' effect is a function of the residual anomaly itself,"

(2) the procedures have no physical bases,

and

(3) the results are dependent on the prescribed procedure.

The reviewer feels the first criticism is certainly valid. The second is not. Vajk admits that Henderson & Zietz (*Geophysics*, October, 1949) demonstrate that the simple nine-point averaging method gives results that are dimensionally different but numerically proportional to second vertical derivative values. Actually the most popular use of the template method is for the computation of the second vertical derivative (see, for example, Evjen (*Geophysics*, January 1936), Peters (*Geophysics*, July 1949), Elkins (*Geophysics*, January 1951)) which is a definite physical basis. The third criticism is valid also. However, the arbitrary nature of the procedures may be construed as an advantage instead of a disadvantage. The choice of the grid size, array pattern, and coefficients is itself a personal interpretation designed to emphasize anomalies of a certain specified nature and discriminate against the remainder or the "regional." After the initial decision is made, the operation becomes mechanical and routine. This is perhaps the chief merit of the grid method inasmuch as the operation can be carried out by unskilled labor together with computing machines. Another merit is that the operation sharpens anomalies and separates them into anomalies of positive and negative sign. In other words, a "zero" contour is established. Such a map has a general, admittedly superficial, usefulness by the very nature of its appearance; and it has quantitative usefulness by affording the opportunity of making certain specified measurements on the derivative values themselves.

There apparently are sharp differences of opinion regarding the regional correction between the "smoothing" school on one hand (Vajk) and the "mechanical" school on the other (for example, Elkins, op. cit.). It is regrettable that both schools are deficient by not presenting a complete and comprehensive discussion of the problem. The "smoothers" disregard what might be called the "functional merit" of the mechanical methods. The "gridders" imply, at least, that their operations are objective; and their papers erroneously suggest that their system is a cure-all. Actually, there are elements of truth on both sides and a more correct approach to the problem of the regional may be made by combining these separate elements into one unified system of operations.

NELSON C. STEENLAND

PUBLICATIONS RECEIVED

Listed below are all publications received at the business office of the society on subscription and through exchange for *Geophysics* since publication of the last issue. Periodicals indicated by the asterisk (*) have been forwarded to the Standing Committee on Reviews, and will be placed in the permanent depository of the society at the University of Tulsa Library. These publications are available for loan to members of the society on application to the business manager. Other publications will be held for a short time at the business office. Disposition of books is by direction of the Standing Committee on Reviews.

Periodicals

American Journal of Science, Vol. 249, No. 12 (December, 1951); Vol. 250, Nos. 1 & 2 (Jan. & Feb., 1952)
**Boletin de la Asociacion Mexicana de Geologos Petroleros*, Vol. 3, No. 3–4, Mar.–Apr., 1951)
**Bulletin of the Hungarian Geological Society*, Vol. 81, No. 7–9 (1951)
**Bulletin of the Seismological Society of America*, Vol. 41, No. 4 (Oct., 1951)
Economic Geology, Vol. 46, No. 8 (Dec., 1951)
**Erdöl und Kohle*, Vol. 4, Nos. 11 & 12 (Nov. & Dec., 1951)
**Geofisica Pura e Applicata*, Vol. 20 (July–Dec., 1951)
**Glasnik Matematicko, Fizicki i Astronomski*, Vol. 6, No. 4 (1951)
Institute of Petroleum Review, Vol. 5, No. 60 (Dec., 1951)
Journal of Applied Physics, Vol. 22, No. 12 (Dec., 1951)
Journal of Geophysical Research, Vol. 56, No. 4 (Dec., 1951)
Journal of the Institute of Petroleum, Vol. 37, Nos. 335 & 336 (Nov. & Dec., 1951)
*Nafta, Vol. 7, Nos. 10, 11 & 12 (Oct., Nov. & Dec., 1951)
*Nuclear Science Abstracts, Vol. 5, No. 23 (Dec. 15, 1951); Vol. 6, Nos. 1, 2 & 3 (Jan. 15, Jan. 31 & Feb. 15, 1952)
**Proceedings of the Cambridge Philosophical Society*, Vol. 48, No. 1 (Jan., 1952)
**Quarterly Journal of the Geological Society of London*, Vol. 107, No. 1 (Dec. 27, 1951)
Review of Scientific Instruments, Vol. 22, Nos. 11 & 12 (Nov. & Dec., 1951); Vol. 23, No. 1 (Jan., 1952)
**Science*, Vol. 115, Nos. 2975 through 2982 (Jan. 4 through Feb. 22, 1952)
**Scientific Monthly*, Vol. 74, Nos. 1 & 2 (Jan. & Feb., 1952)
**Rocznik Polskiego Towarazystwa Geologicznego*, Vol. 20, Nos. 3 & 4 (1950)
**Technical Data Digest*, Vol. 17, Nos. 1 & 2 (Jan. & Feb., 1952)
**Tellus*, Vol. 3, No. 3 (Aug., 1951)

Books

Proceedings of the World Petroleum Congress, Sec. 1 & Sec. 2
Low, Julian W., *Plane Table Mapping*, Harper & Bros. (1952)
Dobrin, Milton B., *Introduction to Geophysical Prospecting*, McGraw-Hill (1952)

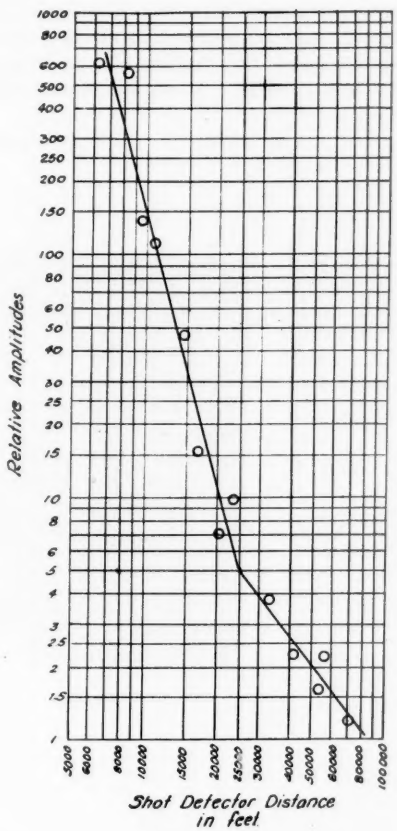
DISCUSSIONS AND COMMUNICATIONS

LETTER TO THE EDITOR

For some time the geologists and geophysicists have been seeking additional aids in the identification of a subsurface bed by measurements from the surface. The graph below suggests that the attenuation of the seismic wave will supply an additional parameter which should aid in the identification.

The data plotted is from the Cherry-Enyu profile of the seismic refraction survey of Bikini Atoll reported by Dobrin, Perkins and Snavely in the *G. S. A. Bulletin*, Vol. 60, (1949) p. 807. The graph shows the variation of amplitude versus distance of the first arrival seismic pulses having frequencies from 9 to 10.5 cycles per second.

At shot-detector distances of 6,000 feet to about 25,000 feet the first arrivals were pulses which had travelled horizontally through calcareous sediments with a velocity of 11,000 feet/sec. From about 35,000 feet to 70,000 feet the first arrivals were travelling with a velocity of 17,000 feet/sec



Amplitude of 1st Arrivals
(frequencies 9 to 10.5 ~/sec)
Versus
Shot Detector Distance.

through what is believed to be igneous rock. In the first case the pulse has passed down through the first layer and has been refracted horizontally in the second layer and is spreading out with a cylindrical wave front. In the second case the pulse has gone down through the first two layers and has been

refracted horizontally in the third layer where it spreads out with a cylindrical wave front. In both cases the relationship of the amplitudes at two points on one of the segments can be expressed by the formula:

$$A_2 = A_1 (r_1/r_2)\ \epsilon^{-k(r_2-r_1)}$$

in which A_1 and A_2 are the amplitudes at distances r_1 and r_2 and k is the absorption coefficient. The value of k can be calculated by:

$$k = (\log A_1 r_1 - \log A_2 r_2)/(r_2 - r_1)$$

In the case at hand the average values for the coefficient are:

Calcareous sediments: 0.2 per 1,000 feet.

Igneous rock: 0.003 per 1,000 feet.

Only meager data on attenuation of seismic waves of such frequencies as used in prospecting are available and probably the values of the coefficient in some sediments will be found to be identical but it is believed that it is most unlikely that the seismic velocities and the absorption coefficients will be identical simultaneously. Furthermore it is suggested that a large decrease in porosity in a sediment should be evidenced by a decrease in the coefficient and an increase in the seismic velocity.

Such measurements must be made with care and require seismometers to be carefully calibrated either absolutely or relative to each other. If those seismographers having the necessary facilities would make measurements of the velocity and absorption in such refracting horizons as are available and positively identified and either publish or send in the results, it would soon be evident if the uses of the absorption coefficient suggested above are feasible.

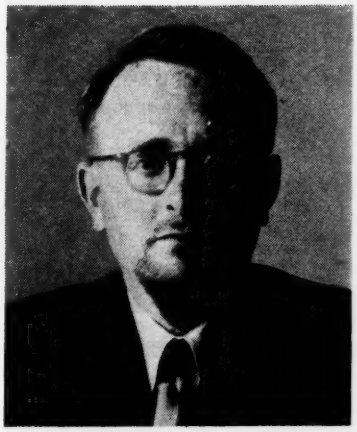
B. PERKINS, JR.

Arlington, Virginia
December 5, 1951

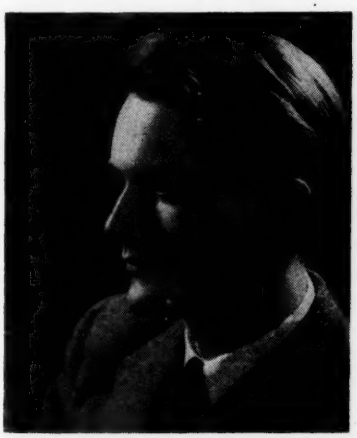
EDITOR'S NOTE: In a recent letter Mr. Perkins writes that he has learned that in 1951 Iv. V. Vasilev published a paper in *Akad. Nauk S.S.S.R. Izv. Ser. Geofiz.* No. 4 entitled "Determination of Absorption Coefficient of Seismic Waves" in which the same suggestion is made.

CONTRIBUTORS

D. I. GOUGH was born in Port Elizabeth, Union of South Africa, on June 20th 1922. He received a B.Sc. degree from Rhodes University College in 1942 and then spent three years in the army as a radar technician. In 1946 he returned to Rhodes University College and in 1947 graduated M.Sc. He then took up his present position as officer in charge of the Applied Geophysics Section of the South African National Physical Laboratory. In this position he is permanently attached to the Bernard Price Institute of Geophysical Research. In 1948–1949 he worked with Professor A. L. Hales on a primary gravity survey of Southern Africa using pendulums. He is now working on an investigation of the "reversed" magnetisation of the rocks of the Pilansberg dyke system. The subject-matter of the present paper is to be submitted as a Ph.D. thesis to the University of the Witwatersrand.

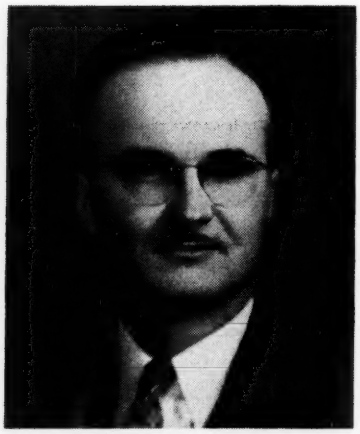


D. I. GOUGH



FRASER GRANT

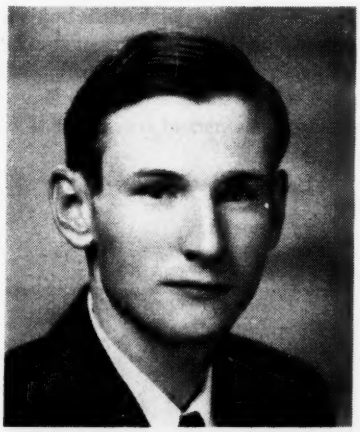
Fraser S. Grant was born in Toronto, Canada, in 1926. He attended St. Andrew's College, where he was gold medallist at the Senior Matriculation in 1943. He entered Honours Mathematics and Physics at the University of Toronto later that year on a scholarship, but completed only one year before transferring to the Faculty of Engineering. He graduated with the B.A. Sc. degree from Engineering Physics in 1948, and in the following year received the M.S. degree in Physics at the University of Illinois. In 1951 he received a Ph.D. under the Department of Physics at the University of Toronto, for work on the further development of geophysical interpretation. At the present time, he is completing a temporary appointment as a research associate at the Geophysics Laboratory of the University of Toronto, and he expects to spend the coming year as an associate of the Department of Geophysics at the University of Cambridge under a reciprocal arrangement between the two Universities.



R. W. MOSSMAN

R. W. MOSSMAN received his A.B. degree from Columbia University in 1935. He worked with the Oklahoma Geological Survey and for the Geophysical Research Corporation, then returned to Columbia where he received his M.A. degree in geology in 1939. He joined Seismograph Service Corporation in 1939 as computer, became party chief in 1942, and since 1944 has been party supervisor for that organization.

Mr. Mossman is a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, American Geophysical Union, Geophysical Society of Tulsa, and the Tulsa Geological Society.



W. C. PRITCHETT

W. C. PRITCHETT received his B.S. in Electrical Engineering from the University of Colorado in 1946 and his M.S. from the University of Texas in 1948. He was then employed by The Atlantic Refining Company in their Production Research Department in Dallas, where he is now located.

BEN R. RUMMERFIELD

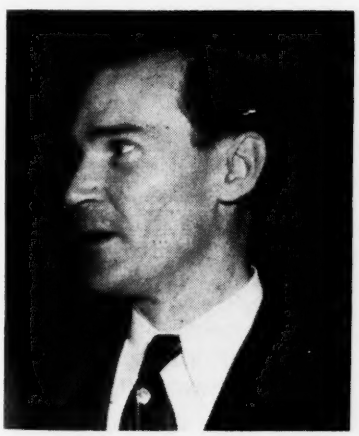
BEN F. RUMMERFIELD was graduated from the Colorado School of Mines in 1940 with a degree of geological engineer, having majored in geophysics. He was employed by Seismograph Service Corp. as a rodman and advanced to seismic party chief, working in a major portion of the geological provinces of the United States. In 1945, he went to Venezuela in the capacity of seismic supervisor. He returned to the United States in the fall of 1947 and completed the Advanced Management Program at the Harvard Graduate Business School. He was then transferred to Mexico where he worked for three years as assistant manager and seismic supervisor. During this period he was instrumental in setting up and operating the first off-shore work done in Mexico in the Bay of Campeche. He also assisted in the establishing of radioactive well logging in Mexico. He joined Century Geophysical Corp. in July, 1950, as manager of seismic operations in the United States and Canada. In October, 1951, he was appointed vice presi-

dent and a member of the Board of Directors of Century Geophysical Corp., which position he now holds. He is a member of the S.E.G., A.A.P.G., American Geophysical Union, Asociacion Mexicana de Geologos Petroleros, Sigma Gamma Epsilon, and Blue Key.

BART W. SORGE

BART W. SORGE received his B.A. and M.A. degrees in Physics from U.C.L.A. in 1933 and 1934. Upon graduation, his geophysical experience began with the Rieber laboratories as a development engineer and later observer and party chief. Since 1938 he has been employed by the United Geophysical Company, serving as development engineer and party chief until 1943, and as a geophysical supervisor until 1947. Since that time he has been a vice president and chief engineer for the same company.

He is a member of the Society of Exploration Geophysicists and the American Association of Petroleum Geologists.



GILBERT SWIFT

GILBERT SWIFT received his B.S. degree in electrical engineering in 1933 from the University of Pennsylvania. From 1935 to 1940 he was engaged in the development of electronic measuring instruments at R.C.A. In 1940 he resigned to join the newly formed Well Surveys, Inc. at Tulsa, participating in the development of the first commercial radioactivity well logging service. During the period 1942 to 1946 he served as Officer in Charge, Direction Finding & Intercept Section, Signal Corps Engineering Laboratories. He attained the rank of Major and was transferred to inactive duty in January 1946, at which time he rejoined Well Surveys, Inc., being designated chief engineer in 1947. In 1949 he was awarded the professional degree of Electrical Engineer by the University of Pennsylvania. Mr. Swift is a member of Sigma Tau, Eta Kappa Nu, Society of Exploration Geophysicists, and the Institute of Radio Engineers.

H. M. THRALLS

H. M. THRALLS has had more than 18 years' experience in seismograph work and has been associated with Seismograph Service Corporation since 1936. He was made chief geophysicist in 1945 and vice president in 1949. He received his B.S. and M.S. degrees in physics in 1932 and 1935, respectively, from Oklahoma University.

Mr. Thralls is a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, American Geophysical Union, Geophysical Society of Tulsa, and the Tulsa Geological Society.

J. P. WOODS

J. P. WOODS graduated from The University of Texas in 1925 with the degree of B.S. in Electrical Engineering. He received the M.S. degree in 1930 and a Ph.D. in Physics in 1932 from the same University. From 1933 to 1940, he was in the Geophysical Laboratory of The Shell Oil Company. From 1941 to 1944, he was in the Radio Research Laboratory of Harvard University. Since 1944, he has been Supervisor of the Geophysical Laboratory of The Atlantic Refining Company.

Dr. Woods is a member of The Society of Exploration Geophysicists, The American Geophysical Union, and The Seismological Society of America.

SOCIETY ROUND TABLE

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CARL L. BRYAN — RICHARD A. GEYER

DIRECTORS OF THE AMERICAN GEOLOGICAL INSTITUTE

L. L. NETTLETON (Nov., 1952) — ANDREW GILMOUR (Nov., 1953)

REPRESENTATIVE ON DIVISION OF GEOLOGY AND GEOGRAPHY
NATIONAL RESEARCH COUNCIL

L. L. NETTLETON, Gravity Meter Exploration Co., Houston, Texas (June, 1952)

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

ACTIVE

George Collin Agnew (J. A. Armstrong, U. J. Chaput, C. H. Acheson)
Richard Warren Aldrich (J. C. Menefee, C. G. Dahm, R. M. Nugent)

Richard Arthur Baile (Karl Dyk, M. B. Widess, H. E. Itten)
Bert Lee Bass (R. L. Lay, C. R. Wallace, Will Silva)
Kenneth Charles Bayer (Stanley E. Giulio, R. R. Thompson, E. M. McNatt)
Carlyle Smith Beals (Ernest A. Hodgson)
Harold C. Bemis (Curtis H. Johnson, O. F. Van Beveran, S. C. Stoneham)
Wayne Z. Burkhead (R. J. St. Germain, R. O. Wingett, Carroll M. England)
Will Henry Burt (Clark E. Allen, J. B. Nichols, K. E. Etheridge)
Louis Cagniard (Leon Migaux, Milton B. Dobrin, C. Hewitt Dix)
Spencer Claus (K. E. Burg, C. H. Green, E. A. Kiesler)
Paul James Cline (George A. Grimm, Charles C. McBurney, R. D. Arnett)
Francis Albert Collins, Jr. (L. P. Whorton, H. F. Dunlap, J. P. Woods)
Harvey Franklin Cooper (Stewart Cronin, Grant M. Roberts, V. E. Prestine)
Douglas Sloan Copeland (Leo J. Peters, F. T. Allen, M. D. Butler)
Horace Victor Copeland Jr., (D. R. Dobyns, O. H. Armstrong, W. B. Brinnon)
Johnnie Carlos Davis (H. M. Thralls, R. W. Mossman, H. H. Andrews)
Geoffrey Francis Dod (E. J. P. van der Linden, A. A. Fitch, Noel Frost)
Chester Ross Dodd (Hugh Porter, Jr., H. C. Smith, E. F. Zagst)
William Harry Doughty (Sidon Harris, T. O. Hall, Wayne H. Denning)
James Penrhyn Duncan (George E. Wagoner, W. W. Clark, Ralph H. Akin)
Howard Andrew Durbin (Sigmund Hammer, Ralph B. Ross, Louis F. Melchior)
George Latrell Ellis (Lynn D. Ervin, Karl Dyk, Wallace D. Ratliff)
Frank Irvin Garrette (Fred G. Knight, H. M. Thralls, R. W. Mossman)
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Andrew Sheldon Gibson (John A. Armstrong, U. J. Chaput, C. Harold Acheson)
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Charles Edward Greener (Glenn M. McGuckin, D. R. Dobyns, Rex H. White)
Joseph William Hammond (J. E. Hawkins, R. S. Finn, H. M. Thralls)
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Dewitt Pierce Fleming (Audio G. Harvey, George Augustat, Ewin D. Gaby)
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William Turk Gilland (C. Edwin Riddell, Wayne H. Denning, Flint Agee)
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Esca Ivan Head (J. C. Heggblom, R. B. Kerbow, J. T. Murrell)
James Douglas Keese (Roy L. Lay, D. H. Scott, N. J. Lea)
Randall Ross Lemaster (Frank B. Smith, W. L. Homan, L. D. Dawson, Jr.)
Henry Hiroshi Nogami (O. C. Clifford, Jr., E. L. DeLoach, C. H. Hightower)
Walter Leonard O'Toole, Jr. (H. V. W. Donohoo, C. M. Marquardt, P. J. Shenon)
Warren Nelson Pearce (Miller Quarles Jr., K. A. Robertson, John Hoffman)
Richard Hoyt Rainey (C. H. Green, F. J. Agnich, K. E. Burg)
Robbie Gene Rutherford (H. E. Itten, C. J. Long. O. W. Anderson)
Antonio Maria Selem (Tiziano Rocco, A. A. Fitch, E. J. P. van der Linden)
James Allen Standridge (H. N. Goodell, C. E. Riddell, M. W. Quarles Jr.)
Henry Clay Towles, Jr. (M. C. Kelsey, M. P. Jones, J. F. Rollins)
D. J. van Nostrand (W. B. Robinson, H. E. Prokesh, Sigmund Hammer)
Howard Ava Willis (H. E. Itten, C. J. Long, Karl Dyk)
Edward Karol Francis Zarudzki (E. J. P. van der Linden, J. K. Ziegler, P. I. Bediz)
Richard Franklin Zimmerly (R. L. Lay, C. S. Johnson, F. F. Lambrecht)
Douglas Dale Barman (James B. Macelwane, S.J., Roy L. Lay, C. R. Wallace)
Richard Oliver Beightol (V. L. Jones, T. S. Green, F. R. Coryn)
Theodore Edward Drews (R. L. Geyer, Henry Chang, J. V. Roberts)
William Robert Hessi, Jr. (F. W. Oudt, G. A. Burton, James B. Macelwane, S.J.)
Wayne Harold Jackson (John C. Hollister, Ralph C. Holmer, Albert W. Musgrave)
Clyde William Kerns (Harry Stommel, Ralph Holmer, W. S. Levings)
James Ade Kurfess (Frank R. Klima, Miller W. Quarles Jr., L. A. Martin)
Salvatore A. LaGreca (J. D. Keese, F. R. Coryn, D. H. Scott)
John Alexander MacMillan (C. H. Green, C. M. Moore, Jr., T. A. Halbrook)
Eric Best Manchee (P. P. Gaby, F. A. Hale, Cecil H. Green)
John C. Pflueger (A. H. Smith, Robert Dyk, Cecil H. Green)
John C. Roller (F. A. van Melle, L. F. Uhrig, B. S. Flowers)
D. S. Seabrooke
Darrell Eugene Smith (H. V. W. Donohoo, G. V. Dunn, D. W. Ratliff)
Robert Peter Vitale (Philip F. Cerveny, David M. Weber, W. B. Robinson)
Marvin Lee Wagoner (Homer L. Heggy, Harrison E. Stommel, Fred J. Agnich)
Hartmut Arno Winkler (William D. Crozier, John Harty, Charles R. Holmes)
Thomas Canby Woodward (Sigmund Hammer, Mark D. Butler, L. W. Gardner)

REINSTATEMENTS TO ACTIVE

Harry M. Cooper (C. J. Harvey, L. L. Nettleton, L. A. Martin)
Ernest A. Pratt.

ANNOUNCEMENT REGARDING MEMBERSHIP LIST

By Executive Order 267, dated May 1, 1951, the business office was authorized to purchase the Remington Rand Flexoprint system for maintenance and publication of the Society's Membership List. This unique system has been installed, eliminating the cumbersome card-file method of maintaining membership records, and at the same time providing a "perpetual manuscript" of the Membership List which can be reproduced by photolithography. The same general appearance will be retained, but the Membership List will be published separately and sent without charge only to members of the Society.

CONSULTING GEOPHYSICISTS AND SOCIAL SECURITY TAXES

Quoted below is a ruling of the Commissioner of Internal Revenue which will be of interest to all consulting geologists and geophysicists. It concerns the payment of Social Security taxes by self-employed members of the profession. As far as is known this is the first ruling of this type to be given, and the American Geological Institute has requested that it be published.

U. S. TREASURY DEPARTMENT
Washington 25, D. C.

Commissioner of Internal Revenue
IT:RP:TR
KVN-1

February 21, 1952

Dear Dr. Delo:

Reference is made to your request that you be furnished with a ruling relative to the status of geologists under the Social Security Act amendments as added to the Internal Revenue Code under the circumstances as outlined in a letter dated January 18, 1952 from Mr. J. V. Howell, Tulsa, Oklahoma.

The information submitted to this office indicates that consulting or independent geologists, particularly in the oil industry may be divided into (a) those whose income is wholly or chiefly from professional fees paid in cash, (b) those whose fees are partly or wholly paid in interests in drilling deals, in royalties, over-riding royalties, or oil payments, (c) and petroleum geologists who come under (a) and (b), their exact status varying from year to year; that as a general rule, consultant geologists have not registered as professional engineers except in those cases where they have found it necessary to prepare reports for such bodies as the S.E.C. and those who registered are in a different category from the vast majority who are not. Advice was specifically requested as to what degree income of a geologist derived from fees and from the various types of oil income, particularly over-riding royalties and working interests, which are the most common forms of remuneration, would be excluded from net earnings from self-employment under the provisions of the Code.

Section 481(a) of the Internal Revenue Code, as added thereto by the Social Security Act amendments of 1950, defines, for the purposes of Subchapter E, the term "net earnings from self-employment" as "gross income derived by an individual from any trade or business carried on by such individual, less the deductions allowed" by Chapter 1 of the Code, "which are attributable to such trade or business," . . . ; with the exceptions noted therein.

Whether or not a given individual is engaged in a trade or business, who for employment tax purposes has been determined not to be an employee, must necessarily depend upon the facts existing in the particular case. It might be stated as a general rule that a person who is regularly engaged in an occupation or profession for profit which constitutes in whole or in part his livelihood and who is not regarded as an employee for employment tax purposes is engaged in a trade or business. Said individual will be regarded as being self-employed under the Social Security Act amendments of 1950 if the business in which he is engaged does not come within the exclusions as stated in section 481(c) of the Code.

Section 481(c) of the Code provides that the term "trade or business" when used with reference to self-employment income or net earnings from self-employment, shall have the same meaning as when used in section 23, Chapter 1, of the Internal Revenue Code except that such term shall not include—

> (5) The performance of services by an individual in the exercise of his profession as a physician, lawyer, dentist, osteopath, veterinarian, chiropractor, naturopath, optometrist, Christian Science practitioner, architect, certified public accountant, accountant registered or licensed as an accountant under State or municipal law, full-time practicing public accountant, funeral director, or professional engineer; or the performance of such service by a partnership.

If the services performed by a consulting or independent geologist are so integrated with the

services performed by an individual in the exercise of his profession as an engineer they are excluded under the provisions of section 481(c) of the Code and the net income therefrom would not be net earnings from self-employment under the self-employment provisions of the Code.

Following are the answers to the questions in the order in which presented by Mr. Howell:

(a) If the activities of a professional or consulting geologist do not come within the exclusions set forth in section 481(c) and the trade or business tests are met the professional fees paid in cash for taxable years beginning on and after January 1, 1951 would be net earnings from self-employment under section 481(a) of the Code.

(b) If the exclusion provided in section 481(c) (5) of the Code is not applicable and the trade or business tests are met, the value of the interest in the drilling deals, the value of the right to receive royalties or over-riding royalties and the value of the payment in oil would for taxable years beginning on and after January 1, 1951 constitute net earnings from self-employment under the self-employment provisions of the Code.

(c) A ruling in the case of a taxpayer coming under this classification would have to be based upon the particular facts present in his case.

Very truly yours,

E. I. McLarney (signed)
Deputy Commissioner

AMERICAN GEOLOGICAL INSTITUTE

At this time, the twelve constituent societies of the A.G.I. are: A.A.P.G.; A.G.U.; A.I.M.M.E.; Assn. of Am. State Geologists; G.S.A.; Mineralogical Soc. of A.; Paleontological Soc.; Seismological Soc. of A.; S.Ec.G.; S.E.P.M.; S.Ex.G.; Soc. Vet. Pal. The Institute is organized as an instrument of the National Research Council which is an agency of the National Academy of Sciences. Its office space and other substantial assistance are supplied by the National Research Council.

The Executive Director of the Institute has recently issued a general report on activities during the period November, 1950, to February, 1952. A number of items of this report have been included in previous summaries of Institute activities in *Geophysics*. In order to bring our membership up-to-date, the items of general interest or special interest to the S.E.G. are summarized herewith.

The financial support of the Institute is approximately in balance with its present requirements but the enlargement of its activities, which its Directors consider highly desirable, will depend on increasing that support. At the present time, the most promising avenues of such support appear to be through the development of "Associates," i.e., industrial users of geology, and through Institute publications. In the latter part of 1951, some 15 "Associates" pledged a total of about $5,000.

The financial status of the Institute (to the end of its fiscal year, June, 1951), condensed somewhat from the official report,* is as follows:

Income		*Expenses*	
A.A.P.G.	$ 2,500.00	Salaries	$ 9,126.54
G.S.A.	5,000.00	(One-half of salary of Exec. Dir. and typist shared with Nat. Res. Council; full salary of Secretary)	
Mineralogical Soc.	400.00		
Seismological Soc.	50.00		
S.E.P.M.	50.00	Travel	1,615.10
S.Ec.G.	1,000.00	Costs of Publications	2,339.82
Individuals and Local Societies	1,910.00	Phone, Wire, Postage	1,076.41
Sale of Publications	3,439.83	Miscellaneous	838.98
Miscellaneous	814.05		
	$15,186.88		$14,996.85

Recent special publications of the Institute have included "Outstanding Aerial Photographs in North America" and "Suggestions for a Program of Public Education." The former has been particularly well received and reprinted once since the original issue. The monthly "News Letter" is being published regularly. It is distributed to the officials of all Member societies, presidents of local societies, to students, and to some local societies who have group subscriptions.

* Editor's note: This statement was prepared prior to receipt of $1,000 income from the Society of Exploration Geophysicists.

Publication projects under way include:

(a) A geological career booklet which is being printed and will be distributed shortly to geological organizations, state surveys and geological departments for distribution to high school vocational advisers and students. A committee has been organized for the preparation of a more elaborate and illustrated booklet.

(b) The "Directory of Geological Departments," originally prepared by the Research Committee of the A.A.P.G., has been taken over by the A.G.I. and a second edition will appear shortly. This has become an annual project of the Institute.

(c) A "Directory of Summer Geology Field Courses" was issued in 1950 and a second edition will be issued this spring. It is planned to continue this on a biennial basis.

(d) The first "Catalogue of Guide Books and Road Logs," issued in June, 1950, is being brought up-to-date and a new issue will appear in the spring of 1952.

(e) A highway strip guide with geological and general information is being prepared experimentally for Highway 75 from Galveston to the Red River.

(f) A report on current non-industrial research in geological science was issued in 1950; it is planned to put this on a biennial basis, with a second issue in 1952.

New publications include:

(a) The "Glossary of Geological Terminology," under the chairmanship of J. V. Howell, is progressing actively. Some 15 partially completed glossaries have been located. The plans for the mechanics of preparation are quite complete and a basis for financing the publication is taking shape. It is anticipated that a book of some 600 pages will contain around 20,000 terms.

(b) A "Journal of Geological Abstracts" is a project obviously of service to the profession as a whole and is of the kind which is a natural one for the Institute to undertake. However, an Abstract Journal comparable to similar ones in chemistry, physics, and biology, which would cost in the neighborhood of $50,000 per year, is far beyond the present resources of the Institute. Consideration is being given to the beginning of such a project through the publication of authors abstracts in pamphlet form through the photolith process. This would be a much less expensive, but quite useful, publication.

(c) Investigations are being continued toward the publication of a general professional magazine somewhat similar to "Chemical and Engineering News" or "Physics Today" which would replace the present "News Letter." It is hoped that such a magazine could be supported through advertising.

The Institute is continuing its program of public information to build up a general appreciation of geology. There is a surprising lack of knowledge of what geology is and can do. This is true in many colleges and is almost universal at the High School level. Any correction of this situation will require much time. Current activities of the Institute in this direction include (a) a survey of geological education, (b) participation in the third annual New England Conference on Earth Science in Secondary Schools, (c) initiation of and assistance in the operation of an "Earth Science Week" in one community in Illinois, and (d) the promotion of the employment of a full time geologist by the extension division of the University of Minnesota.

L. L. NETTLETON

EARL G. DROESSLER NAMED EXECUTIVE DIRECTOR OF RDB GEOPHYSICS AND GEOGRAPHY COMMITTEE

Appointment of Earl G. Droessler as executive director of the Committee on Geophysics and Geography, Department of Defense Research and Development Board, was announced recently by Walter G. Whitman, chairman of the board.

Mr. Droessler has served as staff meteorologist, Office of Naval Research, since 1946, and most recently was Head of the ONR Meteorology Program in the Geophysics Branch of the Earth Sciences Division. He is a native of Dubuque, Iowa.

Mr. Droessler received his A.B. degree from Loras College in Dubuque in 1942, and in the same

year joined the Navy. The year 1944–45 he spent at the Navy post Graduate College, doing advanced work in the field of aerological engineering. He subsequently served as aerological officer at various Naval Air Stations. In April, 1946, he was assigned as assistant research and development officer in the Aerology Office of the Deputy Chief of Naval Operations, and in July, 1946 was assigned to the Office of Naval Research as a meteorologist.

In 1948, Mr. Droessler represented the National Research Council at the meeting of the International Union for Geodesy and Geophysics at Oslo, Norway. During 1950–51 he returned to Oslo for further work in his field at the University of Oslo, as the holder of a Fulbright Fellowship. He is a Ph.D. candidate in geophysics at the University of St. Louis.

GULF COAST REGIONAL MEETING

The Society of Exploration Geophysicists, Houston Section, will hold its annual Gulf Coast Regional Meeting May 29–30, 1952, in the Crystal Ballroom of the Rice Hotel, Houston, Texas. Technical sessions will be held both days of the two-day meeting. Most of the papers will be of a geophysical nature, but several papers will be presented on geological subjects through the cooperation of the Houston Geological Society.

The Annual Dinner Meeting will be held Thursday evening, May 29. Entertainment will be provided and new officers of the Section will be installed. A cocktail party will be held prior to the dinner, and all registrants, whether attending the dinner or not, are invited to attend. On Friday evening, May 30, a dance-breakfast will be held with music being supplied by one of the outstanding orchestras of the Southwest. Special entertainment for the ladies will be provided during the two days of the convention.

The Rice Hotel, Houston, Texas, has kindly consented to serve as clearing house for reservations for the convention. All requests for reservations will be taken care of in the Rice Hotel while rooms are available, after which they will be placed in the Texas State Hotel or the Lamar Hotel. Visitors may prefer to contact directly the hotel of their choice.

PERMIAN BASIN SECTION HOLDS ANNUAL MEETING

The first annual meeting of the Permian Basin Geophysical Society will be held at the Scarborough Hotel, Midland, Texas, Saturday, May 17, 1952. The full day of technical sessions will include eight papers, six of which have not previously been presented.

Lester H. Johnson of Honolulu Oil Corp., president of the Midland Section, is in charge of arrangements. G. A. Grimm of Tide Water Associated Oil Co., vice president of the Midland Section, is in charge of the technical program. Paul Reed of Forest Oil Corp., and vice president of the Midland Section is in charge of accommodations; and L. Decker Dawson of Republic Exploration Co., and secretary-treasurer of the Midland Section is in charge of advertising, publicity and finance.

Although plans are as yet incomplete, registration will begin at 8 A.M. and the first paper will be presented at 9 A.M. At the close of the technical sessions, there will be a reception, and in the evening the annual dance will be held. A complete list of the papers will be released at a later date. Members wishing to attend this meeting are asked to apply directly to the Scarborough Hotel for accommodations. Although a large block of rooms has been reserved, members are asked to share double rooms, if possible.

FIFTH EMPIRE MINING AND METALLURGICAL CONGRESS

The Fifth Empire Mining and Metallurgical Congress will be held in Australia from April 12 to May 23, 1953, and subsequently in New Zealand, according to an announcement recently received from the secretary.

The chief object of the Congress is to afford an opportunity for mining engineers, metallurgists, scientists, engineers, and others concerned with the mining and metallurgical industries to meet and discuss technical progress and problems, including the development of the mineral resources of the British Commonwealth of Nations.

Members of the S.E.G. interested in attending the Congress may obtain registration forms by writing to the Secretary, Fifth Empire Mining and Metallurgical Congress, Osborne House, 399 Little Collins Street, Melbourne, Victoria, Australia.

ANNOUNCEMENT

EUROPEAN ASSOCIATION OF EXPLORATION GEOPHYSICISTS FORMED IN THE HAGUE

On 14th December, 1951, the inaugural meeting of the European Association of Exploration Geophysicists took place in the building of the Royal Netherlands Institute of Engineers at The Hague.

Formed at The Hague last June during the Third World Petroleum Congress, this association, with a membership drawn mainly from Europe and representing thirteen countries (viz., East Africa, Belgium, Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, and Great Britain) has already been joined by 320 geophysicists working in Europe and North East Africa.

The headquarters of the Association will be at The Hague. Its Council Members are: Mr. A. van Weelden, Director of Research, De Bataafsche Petroleum Maatschappij (Royal Dutch/Shell Group) —President; Dr. B. Baars (Netherlands)—Secretary-Treasurer; Dr. D. T. Germain Jones (Great Britain)—Vice-President; Dr. A. A. Fitch (Great Britain), Mr. L. Migaux (France), Dr. E. H. Hedstrom (Sweden) and Dr. A. Schleusener (Germany)—Members.

On the day following the inaugural meeting, the President, Mr. A. van Weelden gave an address to members on geophysical activities in Western Europe between 1946 and 1951, and the following six papers were read:

1. "Geometric Problems Originated by Reflection Seismic in Mines" by Dipl. Ing. H. Linsser.
2. "The Design of Electromagnetic Geophones" by Dr. D. T. Dennison.
3. "Gravity Effect of Earth Tides" by Dr. B. Baars.
4. "Earth Tilts and the Flow of Oil Wells" by Dr. R. Tomaschek.
5. "Sur le Calcul de l'Influence Gravimetriques des Structures Defines par les Isobathes" by Mr. V. Baranov.
6. "Some Examples of the Application of Isostacy" by Mr. J. W. de Bruyn.

INSTITUTE OF RADIO ENGINEERS TO MEET

Program and plans for the 4th Southwestern I.R.E. Conference and Radio Engineering Show, scheduled for Houston, Texas, on May 16–17 are nearing completion. In making this announcement general conference chairman G. K. Miller, Schlumberger, Inc., said that an attendance of more than 1,000 was expected for the Texas show.

Among the leading speakers assured for the Conference are: I.R.E. preseident Dr. Donald B. Sinclair, chief engineer of General Radio Corporation; Commander R. A. M. Craven of Craven, Lohnes & Culver, Washington, D. C.; A. Earl Cullum, consulting engineer from Dallas, John Reinartz, Eitel McCullough, Inc.; Col. Edwin White, Federal Communications Commission; and others.

A feature of the two-day conference is split session programming to give maximum time for papers in specialized fields and to allow full coverage of a broad field of interest. Friday, May 16, A sessions will be devoted to Audio and "Ham" Engineering; B sessions to Instrumentation. Saturday's A sessions will cover Broadcast—T.V. and Microwave Communications and U.H.F. and Microwave Communications. The B sessions on Saturday will cover Geophysics and Airborne Electronics and Components.

A strong response from exhibitors promises that every booth of the 48 available will be occupied. Ninety per cent had been contracted for early in March. Audio demonstration space and employment interviewing booths were still available.

Wives of Houston Section members have planned a complete program of sight-seeing and entertainment for visiting wives during the two-day Conference.

DALLAS GEOPHYSICAL SOCIETY ELECTS OFFICERS

At its Annual Business Meeting, December 10, 1951, the Dallas Section elected (left to right): C. G. Dahm, Magnolia Petroleum Company, Secretary-Treasurer; J. P. Woods, The Atlantic Refining Company, President; Milton B. Dobrin, Magnolia Petroleum Company, First Vice-President, and Howard Cobb, The Atlantic Refining Company, Second Vice President. Their terms of office will coincide with the 1952 calendar year.

PERSONAL ITEMS

W. B. AGOCS has advanced to full professorship in Physics and Geophysics at the University of Tulsa.

RAY ZONGKER writes from Tokyo, Japan that he should be eligible to leave the Far East on the 15th of April and will probably fly back home for a discharge at Camp Chaffee, Arkansas. He has managed to keep busy in Japan as Assistant Engineering Officer of the signal battalion that handles the communications for General Ridgway's headquarters but is anxious to be back in his seat for the SEG (Tulsa Section) meetings. Mr. Zongker is on leave from Stanolind Oil & Gas Company.

W. D. BLACK, former party chief for Geophysical Service International at Edson, Alberta, is now chief seismologist in its interpretation office at Peace River, Alberta.

ROSS E. BRANNIAN and JOHN A. MACMILLAN have been appointed party chiefs of geophysical Service International and are operating crews in Peace River and Stettler, Alberta, respectively.

JACK L. STEPHENS, former party chief, has been promoted to supervisor of Geophysical Service International and is in charge of crews operating out of Peace River, Alberta.

W. E. DICKSON, former party chief with Geophysical Service Incorporated in Brazil, is now serving with Geophysical Service International as equipment supervisor in charge of its warehouse and maintenance depot which is being set up in Edmonton, Alberta, Canada.

CALVIN J. SPIVEY, who has served as party chief with Geophysical Service Inc., in Lousiana, is now performing interpretation and review work as Seismologist in Maracaibo, Venezuela.

B. A. HARRIS has been promoted from party chief of Geophysical Service Incorporated in Mexico to supervisor of its border crews with office and residence in McAllen, Texas.

ROY L. FULLER, GEORGE A. HOWARD, D. E. HILL, and JOHN C. PFLUEGER have recently been appointed party chiefs of Geophysical Service Inc.

A. B. CHAPPELL, director and treasurer of Seismograph Service Corporation of Tulsa, recently took a leave of absence from his work because of ill health.

Chappell will retain his position with SSC, but his active duties will be assumed by F. B. LEEDY, assistant treasurer.

Having joined the company in 1934, Chappell has served in various field assignments, as assistant secretary, treasurer, and director. Mr. and Mrs. Chappell plan to spend several months in the Ozarks. They have a son, Richard, who is in the Air Force, stationed at Sheppard Field, Texas.

F. B. Leedy has been with the seismic exploration company since 1934. His experience with SSC includes work in Trinidad, in Argentina as manager and party chief of seismic operations, in the Bahamas, and as vice president of SSC's Canadian operations in Columbia.

Stanolind Oil and Gas Company has announced the establishment of fourteen fellowships for advanced study and research in various fields of petroleum science at twelve colleges and universities for the school year of 1952–1953.

Each of the fellowships is valued at $1,250, plus tuition and laboratory fees, and will be in force for one academic year.

The schools and fields of study selected by the oil company are: Columbia University, New York City, geophysics; University of Kansas, mechanical engineering; Louisiana State University, chemistry, and geology; University of Michigan, chemical engineering; University of Oklahoma, petroleum engineering; University of Pennsylvania, accounting; Pennsylvania State College, petroleum engineering; St. Louis University, geophysics; University of Texas, geology and petroleum engineering; Texas Agricultural and Mechanical College, petroleum engineering; University of Tulsa, petroleum engineering; and Yale University, geology.

The fellowships are available to all qualified graduate students upon application to the respective universities. Selection will be made by the schools in cooperation with Stanolind, with the fellowships being awarded to those students considered most worthy of scholastic aid and best able to carry on advanced study in their respective fields.

Throughout the tenure of the fellowships, company representatives from the various departments interested in the work will maintain contact with the fellows in order to discuss practical as well as theoretical aspects of the problems.

Stanolind makes no reservations whatsoever in regards to patent rights or subsequent employment of fellows with the Stanolind organization. Any benefits derived from the study and research will be made available to the entire industry without cost.

This is the 16th year that Stanolind has granted such fellowships. The program was begun in 1937 with one fellowship at the University of Texas.

JAMES R. WILLCOCKSON has been named field seismograph supervisor in the Central Division Office of Stanolind Oil and Gas Company at Oklahoma City, Oklahoma.

Willcockson joined Stanolind in 1947 as a computer on a seismograph field party. He has a B.S. degree in physics from the University of Tulsa. Before coming to Oklahoma City, Willcockson was serving as a geophysicist in the company's seismic interpretive office at San Angelo, Texas.

Dr. J. P. MINTON of the Field Research Laboratories of the Magnolia Petroleum Company, Dallas, Texas, has been granted a special leave of absence. Dr. Minton has been with Magnolia for the past sixteen years, serving as Director of Geophysical Research, Associate Director in charge of Physical and Exploration Research, and for the past five years as Research Advisor. Dr. Minton will continue to serve the laboratories on a part time basis, but will make his residence at 112 Wellesley Blvd., San Antonio, Texas, with his son M. C. Minton, District Geologist for Great Lakes Carbon Corporation in San Antonio.

Geotechnical Service Corporation announces the election of two new officers at the Annual Meeting of the Corporation, 3712 Haggar Drive, Dallas, Texas. Elected President of the company is JAMES DALE PERRYMAN, Dallas. DR. WILLIAM B. HEROY, JR., Dallas, is elected Vice-President. Directors, in addition to Mr. Perryman, are William B. Heroy, Sr., of Dallas, and Dr. Roland F. Beers, of Troy, New York. Mr. Heroy, Sr. is Treasurer; A. H. Thompson, Secretary and Assistant Treasurer; B. R. Yeager, Assistant Secretary.

The Dallas Geophysical Society sponsored a symposium on electromagnetic wave propagation in the earth at Southern Methodist University in Dallas on Tuesday, February 12. Chairman of the meeting was Dr. DANIEL SILVERMAN, of Stanolind Oil & Gas Co., Tulsa. The program, held at 8 P.M. in the lecture hall of Fondren Science Building on the SMU campus, included prepared papers by W. T. Born, of Geophysical Research Corp., Tulsa; W. J. Yost and R. L. Caldwell, of Magnolia Petroleum Co., Dallas; Dr. R. Maurice Tripp, of Research Inc., Dallas; G. J. Baker, of W. M. Barret, Inc., Shreveport; H. A. Morriss, Jr. and F. M. McGehee, Jr., of United Gas Corp., Shreveport; and W. C. Pritchett, of The Atlantic Refining Co., Dallas. Following presentation of the papers an open discussion was held. Geophysicists, geologists, radio engineers and electrical engineers were invited to attend.

The Rice Institute announces the establishment of the Harry Carothers Wiess Chair of Geology. This Chair was made possible by a gift of $1,570,000 by Mrs. Olga Keith Wiess in memory of her husband, the late HARRY CAROTHERS WIESS, formerly Vice-Chairman of the Board of Trustees of the Rice Institute and member of the Corporation of the Massachusetts Institute of Technology. He was also a Charter Trustee and permanent member of the Board of Princeton University. It is anticipated that the Chair will consist of a full professor of geology and two associates, and will devote its attention particularly to the field of marine geology. It is hoped that the selection of some, at least, of this faculty will be made in time to begin classes in the newly established division in September, 1952.